VOLUME XXXIII NUMBER 1

THE
JOURNAL OF GEOLOGY

January-February 1925

SOME FACTS AND THEORIES CONCERNING LACCOLITHS

GERALD R. MacCARTHY
University of North Carolina

ABSTRACT

While the literature dealing with the general subject of laccoliths is rather large, yet descriptions and theoretical discussions regarding this type of intrusion are somewhat scattered. In the present paper an attempt is made to collect and classify as many of the known facts as possible, to draw a few general conclusions from the facts so arranged, and to present an experimental method of verifying some of these conclusions which has been developed by the author in the geological laboratories of the University of North Carolina.

I. INTRODUCTION

While there have been many discussions of the facts and theories of laccolithic intrusions, yet it would seem that since Gilbert's early monograph on the Henry Mountains there has been no general publication bringing together the diverse facts which have been more recently collected concerning laccoliths. Each author has dealt either with a small phase of the subject, or with the intrusions of a limited area, so that there are almost as many theories as there are students of the subject. So far as the present writer is aware, practically no work of an experimental nature has been attempted, except for the experiments conducted by Jaggar and Howe.[1]

[1] "The Laccoliths of the Black Hills," *Twenty-first Ann. Report Direc. U.S.G.S.*, Part III (1900), pp. 292–94.

Gilbert, in his famous Henry Mountains monograph, has described the laccolith in the following words:

> The station of the laccolite being decided, the first step in its formation is the intrusion, along a parting of strata, of a thin sheet of lava, which spreads until it has an area, adequate, on the principle of the hydrostatic press, to the deformation of the covering strata. . . . . So soon as the lava can uparch the strata it does so, and the sheet becomes a laccolite. With the continued addition of lava, the laccolite grows. . . . . The ground plan approximates a circle, and the type form is probably a solid of revolution. . . . . The laccolite is a greatly thickened sheet, and the sheet is a broad, thin, attenuated laccolite. . . . . A laccolite grows by lifting its cover.[1]

Since the term was first described by Gilbert, the laccolithic type of intrusion has been extended so as to include many injected masses differing widely from his original type forms. Any intrusive mass possessing a floor sensibly parallel to the underlying strata or other plane of weakness, and which is too thick to be considered a sill, is a laccolith in the modern sense of the word, so long as it has actively arched the overlying strata. Thus, the laccolith grades off into the sill, on the one hand, and into the bysmalith,[2] on the other, there being no sharp line of demarcation between these three types of intrusions.

II. FACTS AND THEORIES

1. *Size of laccoliths.*—Laccoliths, to include only well-established occurrences, vary in thickness from a few feet to several thousand feet, while their areal extent may be equally variable. Gilbert has estimated that Mount Hilliers, the largest of the Henry Mountains group, has a vertical extent of 7,000 feet, while its diameter varies from $3\frac{3}{4}$ to 4 miles, making an estimated volume of about 10 cubic miles.[3] Other intrusive bodies, classed by many as laccoliths, are even larger than this: thus the Duluth gabbro intrusive is said to cover approximately 2,400 square miles, with a total volume of some 50 cubic miles.[4] But, in general, the average size of lacco-

[1] G. K. Gilbert, "Report on the Geology of the Henry Mountains," *U.S. Geog. and Geol. Surv. of the Rocky Mt. Region* (1880), pp. 20, 55, 95.

[2] J. P. Iddings, "The Bysmalith," *Journal of Geology*, Vol. VI (1898), pp. 704–10.

[3] G. K. Gilbert, *op. cit.*, p. 20.

[4] F. F. Grout, "The Lopolith," *Amer. Jour. Sci.*, Vol. XLVI (1918), p. 516.

lithic masses would probably lie somewhere between that of Mount Hilliers and a mass one-tenth as great.

Gilbert endeavored to show that the size of a laccolith is a function of the depth at which lateral spreading occurs, pointing out that in the Henry Mountains district the larger laccoliths lie at greater depths than do the smaller ones. The conclusions of Jaggar,[1] however, do not agree with those of Gilbert, for he shows that in the Black Hills region the size of the intrusive bodies is absolutely independent of the depth at which intruded, the largest body under consideration cutting into the Carboniferous, while many much smaller laccoliths are found below in the Cambrian shales.

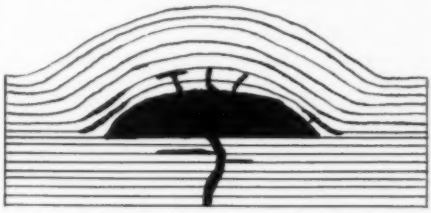

FIG. 1.—Typical laccolith, Henry Mountains. (After Gilbert.)

2. *Shape of laccoliths.*—Aside from irregular and accidental variations, and those pseudo-laccolithic intrusions which have been described under such names as phacoliths, bysmaliths, etc., these bodies fall into two well-marked groups. The variety typified by the Henry Mountains (Fig. 1) is upwardly convex, with high dips along the flanks, and an almost flat crest, while the other type, best illustrated in the Judith Mountains (Fig. 2), is thin edged, with a much sharper crest. So far as the present writer is aware, the only attempt to account for such variations was made by Paige,[2] who showed that increasing viscidity will tend to produce steep-sided, thick lenses, with the bysmalith as the limiting form. It should, however, be remembered that in the case of the Judith Mountains other factors must be considered: the Henry Mountains laccoliths are intruded in thick shale horizons, while in the Judith Mountains the invaded strata are much thinner bedded.

[1] T. A. Jaggar, Jr., "Economic Resources of the Black Hills," *Prof. Pap. 26*, Part I (1904), p. 32.

[2] S. Paige, "The Bearing of Progressive Increase in Viscosity during Intrusion on the Form of Laccoliths," *Journal of Geology*, Vol. XXI (1913), pp. 541–49.

3. *Character and viscosity of the magmas.*—It is generally believed that almost all laccoliths are composed of medio-silicic rocks of the trachyte-andesite class, and while it may be true that the greater proportion of them are acid in character, yet almost every rock type is represented at least once in intrusions of this sort. Thus Daly gives the following list:

> Augite porphyrite, hornblende porphyrite, porphyritic augite diorite, quartz porphyrite, quartz porphyry, sodalite syenite, shonkinite, basic syenite, leucite-basalt porphyry, granite porphyry, rhyolite porphyry, syenite porphyry, grorudite, phonolite, dacite, andesite, etc., etc.[1]

The most striking character of the rocks listed above is not the prevailing acid character, but rather their porphyritic nature, which argues for a considerable degree of cooling, and hence increasing

FIG. 2.—Laccolith and stock, Judith Mountains. (After Weed and Pirsson.)

viscosity before injection. A high degree of viscidity is usually considered essential, yet in several cases we find that typical laccoliths have formed from what must have been rather fluid magmas. Thus in the case of Square Butte and Shonkin Sag[2] a typical laccolith has developed extreme magmatic differentiation, such differentiation as could conceivably occur only in fluid magmas. The further occurrence of basic laccoliths in the Isle of Skye, Minnesota, Oregon, the Rann of Cutch, and elsewhere[3] also points to the conclusion that, given favorable circumstances, rather fluid magmas can produce laccolithic intrusive masses.

4. *Character of the invaded rocks.*—An examination of published descriptions shows that laccoliths are intruded into but two types of formations. Thus both the Judith and Henry Mountains occurrences are found in shale horizons overlain by competent sandstone or limestone strata, while in the Black Hills the tendency

[1] R. A. Daly, *Igneous Rocks and Their Origin*, p. 75.

[2] Weed and Pirsson, "The Highwood Mountains of Montana," *Bull. Geol. Soc. Amer.*, Vol VI (1895), pp. 390–422.

[3] R. A. Daly, *op. cit.*, p. 75.

is to lie along a plane of unconformity, with competent cover-beds of similar character to those mentioned above.

Moreover, the round-arch Henry Mountains type always seems to be developed in thick shale strata, while the sharp-edged, concave-sided Judith Mountains variety appears in strata whose bedding is much thinner. Again, sills seem likewise to be favored by thin-bedded formations.

5. *The conduit.*—In few published descriptions is mention made of the conduit, it being in most cases so situated as to escape direct observation. It is usually assumed, however, that it is of the nature of a dike, and in case of circular and subcircular laccoliths, of small lateral extent, else an anticlinal arch, rather than a quaquaversal dome, would have been formed. As is pointed out by Jaggar,[1] any inclination of the conduit will be reflected in the shape assumed by the intrusive mass, the magmas tending to pile up on the side toward which the conduit is directed, thus producing an asymmetrical lens. This is further brought out in the experimental work of Howe,[2] where it was found that any inclination of the tube through which the material was forced influenced the final shape assumed.

The conduits fall into two chief classes: (*a*) fractures which die out upward by passing into monoclinal folds (as seems to be true in the Henry Mountains), and (*b*) fissures bounded upwardly by planes of unconformity, as is found in the Black Hills laccolith area, there being no record at hand of laccoliths forming where the major fractures reached the surface.

6. *Depth of intrusion.*—Little can be said as to the depth at which intrusions of this type take place, other than noting that it must be sufficiently great to assure enough plasticity to the cover-beds to prevent their rupturing and allowing the magmas to escape through the fissures thus formed. Gilbert[3] estimates that the Henry Mountains masses were intruded at depths ranging from 3,500 to 7,000 feet. Russell[4] has endeavored to prove that sills are a phenomenon belonging to the upper portions of the earth's crust, while other intrusions take place at comparatively great

[1] *Op. cit.*, p. 30. [2] Jaggar and Howe, *op. cit.*, p. 30. [3] *Op. cit.*, p. 86.

[4] I. G. Russell, "On the Nature of Igneous Intrusions," *Jour. Geol.*, Vol. IV (1896), pp. 177–94.

depths, but in the Black Hills region the reverse seems to be the case, for Jaggar states in part: ". . . . In Cambrian thin-bedded strata with many shale horizons sills formed in great numbers. Above lay the thick limestone, ... beneath it formed the principal laccoliths of larger size."[1] That is, the character of the invaded strata played a far larger part in determining the form assumed by the intrusion than did the depth of intrusion.

7. *Apparent temperatures of Magma at time of intrusion.*—From the nature of the case, little can be learned directly of the temperatures of underground magmas, even though we study lavas as they are extruded from volcanoes, since the two cases are very unlike. The best method of approach seems to be through the metamorphic effects produced on the invaded rocks, and in all cases this seems to have been slight. Thus Gilbert described the effect of the intrusive "trachytes" of the Henry Mountains on the country rock in the following words:

> Where the trachytes came into contact with the sedimentaries the latter were more or less altered. . . . . Clay shales were indurated so as to clink under the hammer, ... minute crystals of feldspar had been developed. The sandstones were usually modified in color, and their iron segregated, ... the granular texture was always retained.[2]

A dike a few feet in thickness often produces as great metamorphic effects as this.

Weed and Pirsson[3] also noted that in the Judith Mountains area the metamorphic effects of the intrusions were almost negligible, while Cross pointed out that not only have the sediments adjacent to laccolithic masses been unattacked by heat, but that the temperatures were low enough to prevent caustic action on wall rock or inclusions.[4]

8. *Relation of intrusive masses to overlying beds.*—It seems almost self-evident that any intrusive mass capable of doming the overlying strata will create a dome of about the same character, whatever be the nature of the intrusion, and that little can be deduced regarding the shape and relationships of the buried igneous core

[1] T. A. Jaggar, *op. cit.*, p. 29. [2] G. K. Gilbert, *op. cit.*, p. 60.

[3] *Eighteenth Ann. Report Direc. U.S.G.S.*, Part III (1897), p. 583.

[4] Whitman Cross, *Fourteenth Ann. Report Direc. U.S.G.S.*, Part II (1893), p. 230.

from a consideration of the flexures imparted to the cover-beds. Thus a laccolith, a bysmalith, or an "intrusive stock" such as has been described from the Judith Mountains, will all produce essentially the same type of symmetrical dome, which, unless uncovered by erosive agencies, conceals completely the inner core.

9. *The speed of intrusion.*—There is little field evidence regarding the speed at which intrusions take place, although the general consensus of opinion inclines to the belief that the greater the speed, the thicker and more steep-sided the resulting lens. Thus Pirsson, in discussing the "Intrusive Stocks of the Judith Mountains," ascribes their origin to a so great rapidity of intrusion that any readjustment of internal stress was impossible, and the roofs of the potential laccoliths were broken through by the rising magmas.[1] If this idea is followed out to its logical conclusion, it would appear that slow rates of intrusion should favor sills, greater speeds favor laccoliths, and if the injection takes place with still greater rapidity, stocks may develop.

10. *Forces acting during intrusion.*—Again there seems to be but little direct field evidence, and hence we find a great variety of opinions held by various students. Gilbert[2] gives to the hydrostatic force of the ascending column of magma the full credit for having lifted the cover-beds unaided, while Cross[3] appears to assume that laccoliths will often only form where the invaded beds are under orogenic stress, almost or quite to the point of folding. Hobbs[4] would ascribe to the regional stresses the sole credit, and tries to show that the laccolithic magmas themselves are the result of the fusion of shale beds under relief of pressure caused by the uparching of competent strata, although it is difficult to understand just how a subcircular dome could form under such conditions except where there are evenly distributed radial pressures, the existence of which is problematic, to say the least.

CONCLUSIONS

From a careful survey of the points brought out above, and a comparative study of the recorded opinions of those who have most

[1] Weed and Pirsson, *ibid.*, Part III (1897), p. 587.

[2] *Op. cit.*, p. 95. [3] *Op. cit.*, p. 236.

[4] W. H. Hobbs, *Earth Evolution and Its Facial Expression*, pp. 53–58.

studied the problem, it would appear to the present writer that the following generalized conclusions regarding laccolithic intrusives were justified:

1. The size of laccoliths varies widely within no definite limits, there being no single factor, or any determinable series of factors (unless it be the available supply of magma), upon which it is dependent.

2. The shapes of laccoliths are as variable as their size, and seem to depend upon many interacting factors such as the nature, shape, and inclination of the conduit; the nature and character of the bedding of the invaded rocks; and variations in the viscosity and the speed of injection of the different intrusive magmas.

3. A high degree of viscosity, and especially an increase in viscosity during the period of injection, is probably the most effective single factor in the formation of this type of intrusion, though many typical laccoliths have formed where this factor has been lacking.

4. Most, but by no means all, laccolithic cores consist of medium-acid porphyries. It would appear probable that this type of magma possesses the optimum degree of viscosity for the development of laccoliths.

5. Thick-bedded strata favor the development of the round-dome laccolith, while thin-bedded horizons are more apt to contain sills and the thin-edged, steep-sided Judith Mountains type of laccolith.

6. Laccoliths are found invariably either along shale horizons overlain by competent sandstone or limestone strata, or else they are intruded along planes of unconformity which are immediately followed above by similar competent beds.

7. The nature of the conduit plays a large part in determining the character of the intrusion—fissures passing upward into monoclinal folds, or abutting against horizontal beds resting on planes of unconformity being especially favorable to the formation of laccoliths.

8. Injection of laccolithic masses may take place at any depth sufficient to assure a moderate degree of bending of the beds involved.

9. A fairly rapid rate of intrusion tends toward the production of thick lenses, and in extreme cases to the development of stocks through rupture of the overlying strata.

10. Magmatic temperatures are relatively low, for in all cases noted the contact-metamorphic effects of laccoliths are much less than is usual with other intrusive bodies of equivalent magnitude.

11. The shape and character of the dome formed out of the overlying beds bears little or no relation to the nature of the buried igneous core.

12. The agent which actually domes the covering strata is the hydrostatic force of the ascending magmas, aided by the partial relief of gravitational pressure by orogenic stress, in some, if not in all, cases.

III. EXPERIMENTAL EVIDENCE

In order to test, as far as possible, the conclusions set forth above, and to throw further light upon the mechanics of such intrusions, a series of experiments were carried out in the geological laboratories of the University of North Carolina by the writer; a very condensed account follows.[1]

The intrusion machine used in the experimental work was much like that described by Howe,[2] although developed independently. The essential parts consisted of a sheet-iron pan about 15 inches square, through the center of which was a drilled $\frac{3}{8}$-inch hole. Fitting loosely in this pan was a square sheet of heavy galvanized iron provided with wire handles, and likewise pierced by a hole. The material representing the magma was forced into the layered matter with which the pan was filled by means of an *Alemite* grease-gun, which was furnished with a short extension nipple extending up through the pan and the false bottom, and there secured by a nut, the opening in the iron sheet being just large enough to admit this nut. When set up, the machine consisted of a table upon which the pan rested, the grease-gun armed with its extension nipple, the pan, and the false bottom, which served as a platform upon which to lift out the contents of the pan. The

[1] G. R. MacCarthy, *The Laccolith* (unpublished thesis, *University of North Carolina*, 1924).

[2] Jaggar and Howe, *op. cit.*, pp. 292–94.

machine, taken apart to show its component parts, is shown in Figure 3.

Fine, well-damped sand was used to represent incompetent beds, while the competent strata were formed by very thin layers of plaster of Paris. After a layer of sand had been sifted over the bottom of the pan a sheet of tissue paper was laid over it, the plaster spread as thinly as possible over this paper and covered by a second sheet. This process was repeated until as many layers as were desired had been built up, when the pan was filled to the top with "overburden," wet down, and laid aside until the plaster had had

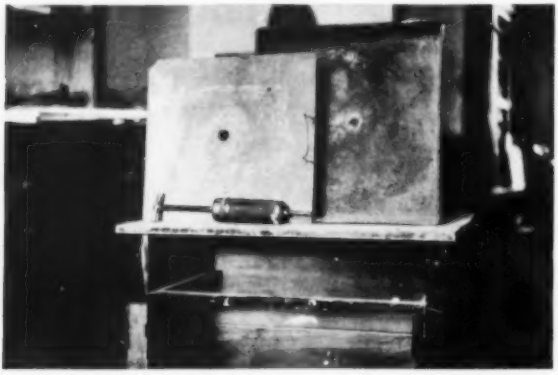

FIG. 3.—Intrusion machine, taken apart to show its component parts

time to set. The excess of water was drained off through a hole left in one corner of the pan for the purpose.

The grease-gun was then filled with a mixture of plaster and water of the desired consistency, colored by the addition of ink or aniline to more readily distinguish it from the plaster strata. The plaster-and-water mixture also contained varying amounts of acetic acid, added to prevent premature set. Each time that the grease-gun was loaded a small dish of the mixture used was set aside and carefully watched to determine the exact time of set; when the desired firmness had been obtained, the false bottom was lifted out by the wire handles attached to it, and the mass of sand and plaster carefully sectioned. These sections were carefully

sketched or photographed (it was found impossible to preserve them entire), and after the strata had been stripped off, the "igneous cores" were given a number and set aside. The sand was then dried, sifted to remove scraps of paper and lumps of plaster, and used over again.

Experiment 1.—A full account is given of this experiment in order to illustrate the methods of procedure; in describing later experiments only the essential features will be noted.

The following strata were placed in the pan: a thin sand layer, a paper-plaster layer, another sand layer, a second paper-plaster stratum, and the pan filled with sand. After a thorough wetting down the plaster was given time to set. The grease-gun was then filled with a mixture of plaster, water, and ink, just thin enough to flow freely, and enough acetic acid added to prevent too quick a set. This fluid was injected as rapidly as possible, the entire operation taking about two minutes. As the handle was turned a low mound formed slowly upon the upper surface of the sand, deep radial cracks developing across its top, although none extended deep enough to permit extrusion of the plaster. Had the injected material risen to the level of these fissures (several of them showed slight differential movement and hence might be called faults) and there solidified, a series of radial dikes much like those which are found in the strata immediately above many laccolith cores would have been formed.

Upon sectioning it was found that a small, very symmetrical, laccolith had developed in the sand layer next above the false bottom, and that the first competent bed had been ruptured, the greater part of the "magma" escaping through the opening thus formed into the sand layer above. Here it had expanded both upwardly and laterally, carrying with it portions torn from the competent plaster-and-paper horizon, and solidifying in the form of an "intrusive stock" which bore a marked resemblance to those figured by Pirsson in his descriptions of the Judith Mountains area (Fig. 2). This phenomenon was doubtless produced by the same cause to which Pirsson ascribes the Judith Mountains stocks, i.e., the speed of intrusion had been too great to permit adjustment of internal stress, and the more resistant upper horizons had been

ruptured by the upward thrust of the ascending "magma." In all later experiments a layer of flexible cardboard was placed over the top of the pan, and a weight of gravel sufficient to prevent the formation of open fissures added. Almost identical results were obtained in later experiments by repetition of the conditions described above.

Conclusions.—If the speed of injection be too great, no true laccolith will form, but the competent beds will be ruptured, the magmas will escape through the opening thus formed, and by lateral and vertical expansion form an umbrella-shaped stock which, though arching the overlying beds like a laccolith, will differ from it in possessing no floor.

Experiment 2.—Conditions similar to those outlined above were reproduced, with the following exceptions: three competent layers were present instead of two, the incompetent sand layers were somewhat thicker, and an overburden of cardboard and gravel was added. The injected material was also somewhat thinner, and twelve minutes were consumed in forcing it into the strata.

This experiment was designed to test the effect of thick, very incompetent beds when serving as horizons of intrusion, the theory being that a thick, steep-sided, and flat-topped laccolith would be developed. That these expectations were justified is shown by Figure 4, which is a photograph showing a section through the intrusive mass which formed. The small hollow at the bottom was caused by the removal of the feed pipe, and therefore is but an accidental feature. It will be noted that while it is by no means exactly like the laccoliths described from the Henry Mountains, the general shape of the intrusion is much more nearly like them than was that formed in experiment 1 before rupture of the roof stratum.

Conclusions.—Thick-bedded, incompetent strata serving as horizons of intrusion will tend to cause the development of thick, steep-sided, flat-topped laccolithic masses, in contrast to the thin-edged, sharp-crested type which is found injected in thin-bedded strata.

Experiment 3.—This was an attempt to study the effect of extremely thin-bedded strata on the shape of masses injected into

them. Again the conditions were similar to those of the former trials, except that in this case tissue-paper bedding planes were supplied to all incompetent (sand) layers. These tissue-paper partings are not shown in Figure 5, which is a cross-section of the injected mass. The original viscosity of the magma, the amount of acetic acid added, and the time taken for injection were identical with those of experiment 2.

FIG. 4.—Section through intrusive mass formed in experiment 2

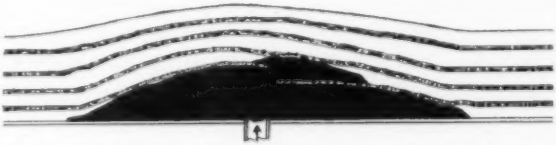

FIG. 5.—Cross-section of the injected mass formed in experiment 3

Upon cutting a section it was seen that a compound laccolith had formed, the injected material spreading out along the false bottom in a rather thin sheet, making a thin, low-slope laccolith in the first sand layer. This shape bears out the idea tested, as the laccolith is of very slight vertical extent, is thin edged, and the marginal slope is gentle. On one side the roof stratum fractured and faulted upward, and through the opening thus created enough of the injected material has migrated upward to form a small but

very symmetrical laccolith in the next incompetent horizon. It should be noted that this secondary laccolith is relatively thick, which may be accounted for by supposing that the plaster had acquired a higher degree of viscosity by the time it reached this level.

Attention should be called to the fact that in this case, as in many of the other experiments, a marked thinning of the beds as they cross the apex of the intrusive mass is to be seen. At the same time the incompetent layers (particularly the thicker ones) are crumpled, distorted, and thickened around the margin of the intrusion, having suffered greatly from the horizontal thrust of the injected liquid.

Conclusions.—Thin-bedded, incompetent strata serving as horizons of lateral expansion of a rising magma tend to split along

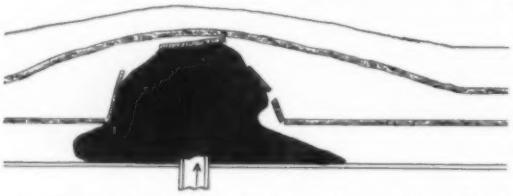

FIG. 6.—Cross-section of the injected mass formed in experiment 4

planes of weakness parallel to the bedding, and thus any laccolith which may form tends to be of the thin-edged Judith Mountains type. Thicker beds will suffer more from lateral thrust, and crumpling, because of the pressure to which subjected, will act as a dull wedge, and will force the overlying competent horizons upward with comparatively steep dips. It also appears that the shape of the external dome gives no indication as to whether or not a compound igneous core has formed below.

Experiment 4.—In this experiment but two competent beds were used, and a very viscid liquid was injected. The liquid plaster was just fluid enough to flow, and a total of seventeen minutes was spent forcing it into the sand layers. Figure 6 is a cross-section of the mass which formed.

It will be noted that the lower competent layer was only slightly domed, but instead has faulted upward, the fault zone being in the

form of a hollow cylinder, and about 2 inches in diameter. The second incompetent layer is much thickened and distorted, having received almost all of the sand pushed out from the space occupied by the injected material, while above it the upper competent stratum is only slightly domed.

This experiment was designed to show that a very thick magma would tend to produce a high and steep-sided lens, and was the thickest intrusive body produced in the entire series of experiments. As the period of injection was somewhat drawn out, it may be that increasing viscosity played some part in achieving this result: later experiments were made to determine the relative effects of absolute and increasing viscosity.

The form of the intrusion thus produced is very similar to those igneous masses which Iddings has called bysmaliths, and is similar in its manner of formation. Iddings says in part:

> When the vertical displacement with faulting is one of the chief characteristics of the intrusion, a distinction from normal laccolithic intrusions should be recognised. In the extreme this would result in the forcing upward of a more or less cylindrical cone . . . . of rock, which might . . . . be arrested at any stage of extrusion and so might terminate in a dome of strata resembling the dome over a laccolith, ... such an intruded plug of igneous rock may be termed a bysmalith.[1]

Conclusions.—It would appear that when the intruding magmas possess great viscosity, and when an increasing viscosity during intrusion is to be expected, an extremely thick injected lens will form. If conditions are extreme, a bysmalith instead of a laccolith may form.

Experiment 5.—In this experiment an extremely thin mixture of plaster and water was used, and about eighteen minutes were spent in injecting it. Two gunfulls were used, one colored blue, and the other red, with the object of determining the final disposition of the material injected at different stages of the intrusive process.

As was expected, a very thin, sill-like mass formed, extremely irregular in shape, and with the later portion of the injected material lying nearest the conduit. The conduit itself was nowhere near the center of the intrusion, but instead lay near one edge, although the thickest portion of the sill was approximately at the center.

[1] J. P. Iddings, "The Bysmalith," *Jour. Geol.*, Vol. VI (1898), pp. 704–10.

The dome impressed upon the cover-beds was immediately above the intrusive core, but was much larger and more regular than the latter, so much so, in fact, that one could not possibly have guessed what sort of intrusion lay beneath.

Conclusions.—The shape of the intrusion does not indicate the location of the conduit, which may occupy a very eccentric position. On the other hand, the greatest thickness lies in the center of the disturbed area. Again it is shown that thin magmas tend to produce sill-like intrusive bodies, and that the dome in the superincumbent strata bears little relation except in *position* to the igneous mass beneath. The material first injected will be found in the distal portions of the body.

Experiment 6.—This sixth experiment again emphasized the fact that stiff magmas produce steep-sided lenses, for an extremely

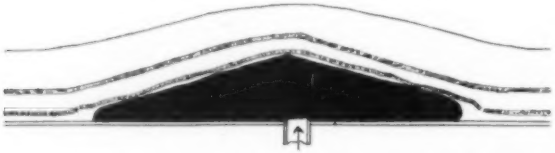

FIG. 7.—Cross-section of symmetrical and rather steep-sided dome formed in experiment 6.

viscid plaster, with considerable acetic acid added (to prevent increase in viscosity during the intrusive process), was used; a very symmetrical and rather steep-sided dome was formed (Fig. 7). As in other trials, the greatest thickness was again near the center of the mass. A marked thinning of the incompetent beds as they pass over the apex of the dome may also be noted.

Experiment 7.—This final experiment was designed to test the effects of open fissures on fluid magmas. A very liquid mixture of hot paraffin and vaseline was forced into an open fissure represented by a series of holes punched through the numerous waxed paper layers which were intercalated in the sand. The pan was filled to the top with these alternating sand and paper layers, and a stiff and inflexible coating of plaster of Paris applied over the entire top.

This liquid wax was injected as rapidly as possible, and with no apparent results; after cooling over night an examination showed that at some time after the close of the intrusive process the liquid, obviously under considerable pressure, had broken its way through the hard plaster covering layer. Forcing its way out through the fissure thus formed, it had spread over the upper surface and there congealed in the form of a miniature lava flow. When a section was cut, it was found that the greater part of the wax had remained in the fissure, and there solidifying, had formed an irregular, spindle-shaped "pipe." There were many short sills extending along the wax-paper partings into the incompetent beds, but in no case were these more than a fraction of an inch in extent. No doming of the overlying beds was apparent.

Conclusions.—This experiment seems to show that in the presence of an open fissure fluid magmas will not arch the overlying beds, but will remain in great measure underground, there forming dikes, necks, or plugs.

GENERAL CONCLUSIONS

From the series of experiments outlined above it would appear that:

1. The more viscous the magma the greater the vertical compared to the lateral extent of the intrusive lens produced, and, conversely, the thinner the magma, the more sill-like the intrusion.

2. Increasing viscosity during the course of the intrusion intensifies the effects of stiff magmas; carried to an extreme, this may result in the production of a bysmalith rather than a laccolith.

3. Excessive speed of intrusion which does not allow time for readjustment of internal stress may lead to the formation of stocks.

4. Extremely thin-bedded strata lead to the development of sills and sill-like laccoliths, while the thin-edged Judith Mountains type of laccolith is formed only in the presence of thin-bedding, and the upwardly convex Henry Mountains type where the incompetent beds are thick.

5. The shape and general character of the intrusive cores are indicated only in the most general way by the dome impressed upon the overlying beds.

6. The location of the conduit may be very eccentric, but the thickest part of the lens will almost always be found near the center of the mass.

BIBLIOGRAPHY

Cross, Whitman, "The Laccolithic Mountain Groups of Colorado, Utah, and Arizona," *Fourteenth Ann. Report Direc. U.S.G.S.*, Part II (1893), pp. 165–238.

Daly, R. A., *Igneous Rocks and Their Origin*, pp. 64–78.

Darton, N. M., "Geology and Water Resources of the Black Hills," *Prof. Pap. 65, U.S.G.S.* (1919).

Gilbert, G. K., "Laccolites in Southeastern Colorado," *Jour. Geol.*, Vol. IV (1896), pp. 816–25.

———, "Report on the Geology of the Henry Mountains," *U.S. Geog. and Geol. Survey of the Rocky Mt. Region* (2d ed., 1880).

Grout, F. F., "The Lopolith," *Amer. Jour. Sci.*, Vol. XLVI (1918), p. 516.

Harker, Alfred, *Natural History of Igneous Rocks*, pp. 64–72.

Hobbs, W. H., *Earth Evolution and Its Facial Expression*, pp. 53–58.

Iddings, J. P., "Bysmaliths," *Jour. Geol.*, Vol. VI (1898), pp. 704–10.

Irving, J. D., "A Contribution to the Geology of the Black Hills," *Annals N.Y. Acad. Sci.*, Vol. XII, No. 8 (1900), pp. 204–44.

Jaggar, T. A., "Economic Resources of the Northern Black Hills." *Prof. Pap. 26, U.S.G.S.*, Part I (1904), pp. 22–23.

Jaggar and Howe, "The Laccoliths of the Black Hills," *Twenty-first Ann. Report Direc. U.S.G.S.* (1900), Part III.

Keyes, C. B., "Mechanics of Laccolithic Intrusion," *Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), p. 75.

Paige, S., "The Bearing of Progressive Increase of Viscosity during Intrusion on the Form of Laccoliths," *Jour. Geol.*, Vol. XXI (1913), pp. 541–49.

Pirsson, L. V., "Petrography and Geology of the Highwood Mountains, Montana," *Bull. 237, U.S.G.S.* (1904).

Russell, I. C., "Igneous Intrusions in the Black Hills," *Jour. Geol.*, Vol. IV (1896), pp. 23–43.

———, "On the Nature of Igneous Intrusions," *Jour. Geol.*, Vol. IV (1896), pp. 177–94.

Weed and Pirsson, "Geology and Mineral Resources of the Judith Mountains of Montana," *Eighteenth Ann. Report Direc. U.S.G.S.*, Part III (1897), pp. 485–587.

———, "The Highwood Mountains of Montana," *Bull. Geol. Soc. Amer.*, Vol. VI (1895), pp. 390–422.

ON THE GENERA CLADOCHONUS AND MONILIPORA[1]

GEORGE H. GIRTY

ABSTRACT

Evidence is offered for believing that *Cladochonus* and *Monilipora* are really the same genus, not only because they have by description essentially the same characters, but also because they probably have the same genotype. *Monilipora* was proposed as an independent genus because Nicholson and Etheridge had an erroneous conception of *Cladochonus*. The *Cladochonus* of those authors and of much current literature doubtfully existed in nature.

The genera *Cladochonus*, *Monilipora*, and *Aulopora* all occur, or at least have been cited as occurring, in the Carboniferous strata of North America. To identify corals of this group, even generically, is usually quite difficult, and to some extent this difficulty is a reflection of the fact that the genera themselves have not been satisfactorily defined and that authors do not agree as to the generic diagnoses of them. The generic outlines are, indeed, far from distinct, but even if this were not so, it is commonly difficult to ascertain in specimens the presence or absence of characters by which the genera were thought to be distinguished. The difficulties and uncertainties in my own experience led me to examine the original sources of our classification, and the results of this examination have seemed of sufficient interest to be made a matter of record. The genera chiefly involved are *Cladochonus* (McCoy, 1847),[2] *Pyrgia* (Milne-Edwards and Haime, 1851),[3] and *Monilipora* (Nicholson[4] and Etheridge, 1879).

McCoy, in his original definition, was interested in discriminating *Cladochonus* from *Aulopora*, and he suggests the following differences. In *Aulopora* the corallites are prostrate and attached for the most part by one side; the individual tubes expand *gradually*

[1] Published by permission of the Director of the U.S. Geological Survey.

[2] *Ann. Mag. Nat. Hist.*, Vol. XX (1847), p. 227.

[3] *Polyp. Foss. Terr. Pal.*, 1851, p. 310.

[4] *Geol. Mag.*, Vol. VI, N.S. (1879), p. 289.

to the mouths, which all open nearly in one direction; they have no regular distance for branching and frequently anastomose. In *Cladochonus* the colony is erect, attached by the base only, which embraces some foreign body; the tubes flare more or less strongly at the aperture; they have a nearly uniform length and are bent in nearly opposite directions; they also have much thicker walls than *Aulopora*. The characters pointed out by McCoy seem to establish *Cladochonus* satisfactorily and to leave little excuse for confusing it with *Aulopora*. It does not appear to me that this diagnosis has been improved upon to any degree by subsequent investigators.

Cladochonus was proposed in 1847. Four years later Milne-Edwards and Haime introduced the name *Pyrgia* for a similar coral. Indeed, *Pyrgia* was subsequently considered to be, and is now generally regarded as, a synonym of *Cladochonus*. Milne-Edwards and Haime, however, seem to have been unaware of McCoy's genus and compared *Pyrgia* only with *Aulopora*. They describe the corallum as being simple, free, trumpet-shaped, pedicellate, surrounded with a strong epitheca. The calice is circular, very deep, showing only obscure traces of septal striae. *Pyrgia* was said to differ from *Aulopora* in being always simple and free. Some explanation seems to be demanded here of the terms "pedicellate" and "free" as employed in this connection. The specimens figured show what appear to be rather strong outgrowths on which the corallites, supposedly simple, were supported well above the object to which they were attached. These were the "pedicels," and the corallites were said to be free in distinction from *Aulopora*, in which the corallites are sessile and cemented for a good part of their length to some other object. Both of these expressions have been misunderstood, I believe, in various ways, and the authors themselves were mistaken in the characters which they wished to designate by them.

The type species of *Pyrgia* is *P. Michelini*, which De Koninck[1] later showed to be not a simple, but a compound, coral, each trumpet-shaped corallite giving off one, two, or even three others by lateral gemmation. The specimen which he figured appears to have a spraylike growth, and its method of attachment is not

[1] *Nouv. Rech. sur les Anim. Foss., etc.*, 1872, p. 153.

known. De Koninck does not mention the peculiar method of attachment ascribed to the genus by Milne-Edwards and Haime, and, indeed, it seems a safe conclusion that the projections which those authors interpreted as props by which the coral was attached to, yet held apart from, the object of support, are really nothing but the stolonal parts of other corallites that have been broken off. Isolated corallites from colonies of *Monilipora Beecheri* that have been broken up present a similar appearance. Milne-Edwards and Haime had only such isolated corallites, and their interpretation was perhaps a natural one, but De Koninck's more perfect material seems to make their interpretation untenable. It should be remarked that the specimens studied by De Koninck as well as those studied by Milne-Edwards and Haime came from the same locality and the same horizon, and there is every reason to believe that they belong to the same species. It appears then that *Pyrgia* as founded upon *P. Michelini* is not a simple, but a compound, coral, and, although we do not know how its spraylike colonies were attached, there is not the slightest evidence for believing that they were attached in the manner ascribed to them by Milne-Edwards and Haime. De Koninck, who accepts the identity of *Pyrgia* with *Cladochonus*, does not describe *Cladochonus* as having this peculiar mode of affixing itself to foreign bodies, yet that character is incorporated into most subsequent descriptions of *Cladochonus*, especially textbook descriptions. It is one of the important differences (on paper) between *Cladochonus* and *Monilipora*—this, too, in spite of the fact that the original description of *Cladochonus* says that the whole polypidom is erect, "attached by the base only, which embraces some foreign body."

The genus *Monilipora* was proposed by Nicholson and Etheridge in 1879. As based upon *M. crassa*, which is unquestionably the type species, *Monilipora* is characterized primarily by its thickened walls and their fibrillated structure. It is also characterized by "its large size, and by its thick, conical, short branches." The mode of attachment "is most usually by the early branches growing in a circle round a crinoidal stem," and such bases apparently supported spraylike outgrowths. In these annular colonies the connecting stolons were "applied directly to the surface of the

crinoid stem" so that they had the mode of growth of *Aulopora*. Indeed, the authors state (p. 291) that in the aberrant *C. crassus* McCoy and the larger forms of *Aulopora*, the habit of the coral is in both cases the same. Furthermore, the coral was not only prone upon the stem of the crinoid, but the stem grew out around it so that bulbous enlargements were formed inclosing the coral whose apertures only appeared at the surface. This peculiarity, however, is of doubtful generic value and may perhaps be considered a character of the crinoid rather than of the coral. Lastly, the inner cavity of the corallites is entirely open and not interrupted by tabulae, structures which were found to be present in both *Aulopora* and *Cladochonus*. Nicholson and Etheridge do not formulate a generic description of *Monilipora* but leave its characters to be inferred from the introductory discussion and from the description of *M. crassa*. Consequently some of the passages quoted above relate more directly, perhaps, to the species than to the genus. It may be remarked that "branches" as used in these quotations means individual corallites, not groups of corallites branching from a basal clump.

The historical review with which Nicholson and Etheridge open their discussion of the structure and relations of *Monilipora* begins with a misapprehension which must profoundly affect the standing of that genus. They say, "The genus Cladochonus was founded by Professor McCoy in 1847 for certain Australian Paleozoic corals, with 'some relations to Aulopora,' but differing, etc." Now a reference to the work in which McCoy's description of *Cladochonus* appeared makes it very doubtful whether after all the genus should not be considered as based on a European instead of on an Australian species, and whether, in fact, the type species of *Cladochonus* is not the very same species that was used to typify *Monilipora*, namely, *C. crassus*. That the generic name *Cladochonus* is at least incidental to McCoy's investigation of some fossils from Australia is, of course, obvious. The significant facts are that in his report the caption "Cladochonus n. g." is followed by a description, and this in turn is followed by a discussion in which it is stated that "*Janeia crassa* and *J. bacularia*, referred to Janeia because of doubt, should now be removed to this genus." Then follows the name

"*Cladochonus tenuicollis*," of which the sole description consists of the words "distinguished by the slenderness of the stems."

It is beyond possibility of contradiction that the first species mentioned under the new generic name *Cladochonus* is *C. crassus*, and also that *C. crassus* (of which McCoy was the original author) was in McCoy's mind in framing the description. Thus he says, "The whole polypidom erect, attached by the base only, which embraces some foreign body." These characters belong to *C. crassus*, and were both described and illustrated by McCoy for that species, but they were apparently not known for the Australian form, *C. tenuicollis*. The thickness of the walls, also, upon which McCoy lays stress, appears to be a character taken from *C. crassus*.

It appears to me then, that both technically and logically, both as being the first species mentioned and as being the species best known to McCoy and the only one cited which showed all the characters ascribed to the genus, *C. crassus* should be considered the genotype of *Cladochonus*. This has the unfortunate consequence of making *Monilipora* a synonym of *Cladochonus*, but I do not see much prospect of retaining *Monilipora* anyway except upon one eventuality.

It is an interesting inquiry how, using the same species as a subject of investigation, Nicholson and Etheridge should have reached the conclusion that *Monilipora* was distinct from *Cladochonus*. The answer is no doubt partly to be found in the fact that Nicholson and Etheridge used a different species in investigating *Cladochonus*. If the characters ascribed by Nicholson and Etheridge to *Monilipora* are compared with the characters ascribed by McCoy to *Cladochonus*, they are found to be almost identical. In both genera the colonies attach themselves by irregular bushy growths around the stems of crinoids, from which spraylike branches were put forth; in both, the corallites have flaring apertures and, so far as known, hollow internal cavities not intercepted by plates or tubulae. The only difference of any moment consists in the wall structure, which Nicholson and Etheridge had investigated and which McCoy had not. McCoy mentions, however, that the corallites had thick walls, a fact from which tentative inferences might have been drawn. If *C. crassus* is accepted as the typical species

of *Cladochonus*, then, of course, *Monilipora* automatically becomes a synonym. If for some reason which is not apparent, *C. tenuicollis* is taken as the typical species of *Cladochonus*, *Monilipora* can be retained provided some differences of sufficient importance are discovered that at present are not suggested, and especially if the Australian species proves to have the walls constructed in a manner decisively different from *Monilipora* as described by Nicholson and Etheridge. In my own judgment the one alternative is impossible and the other unlikely.

Nicholson and Etheridge give an excellent résumé of the literature dealing with these corals, but they seem to have been blind to some of the important facts recorded. Their conception of *Cladochonus* seems to have been derived not from the original description of the genus or a study of the type species, *C. crassus* (which they studied but to a quite different purpose) so much as from a study of *C. Michelini*, with the result that *Monilipora* was distinguished, they thought, by its mode of growth, by the construction of its walls, and by the internal structure.

As to the mode of growth, Nicholson and Etheridge continue the error which originated with Milne-Edwards and Haime in ascribing to *Cladochonus* a mode of growth in which the corallites were supported on short props, and they even cite De Koninck as giving the same character to *C. Michelini* (p. 290), who, they say, described the corallum as furnished with a "pedicle of attachment." This, however, is clearly a misinterpretation. De Koninck does, indeed, use the terms "pedicle" and "pedicillate," but not "pedicle of attachment," and it is obvious from a careful reading of his descriptions that by "pedicle" he does not mean at all the proplike supports which Nicholson and Etheridge had in mind, and which, indeed, Milne-Edwards and Haime indicated by the same word. De Koninck was referring to the tubular part of the corallites below the inflated cups, a part which in *C. Michelini* is especially prolonged. His meaning is absolutely clear and certain, and so far as I am aware the habit so generally ascribed to *Cladochonus* is not only not found in that genus, not even in *C. Michelini*, but is yet to be demonstrated for any auloporoid genus whatsoever.

The structure ascribed to *Cladochonus* by Nicholson and Etheridge, both that of the epitheca and that of the internal cavity,

appears to have been ascertained by personal investigation. The specimens chiefly used for this purpose came from Scotland and were identified as *C. Michelini*, which it will be remembered is the type species of the genus *Pyrgia*, which in general opinion is identical with *Cladochonus*. On such evidence the walls of *Cladochonus* were found to be solid throughout and to lack the reticulated structure of *Monilipora*. The visceral chamber was tubular, crossed in some specimens by a few curved tubulae, but lacking in others any trace of transverse partitions. The figures given by Nicholson and Etheridge certainly do not look much like those of *C. Michelini* given by De Koninck or by Milne-Edwards and Haime, and indeed, the authors themselves frankly admit a doubt whether the specimens sectioned were not isolated tubes of *Aulopora*. Their reasons for considering that they did not belong to *Aulopora* are fairly good, but this has little bearing upon their belonging to the same species or even the same genus as *C. Michelini*.

The conclusions to which this incursion into the literature have brought me are these. The type species of *Cladochonus* is *C. crassus*, and as *C. crassus* is also the type species of *Monilipora*, *Monilipora* is a synonym of *Cladochonus*. The *Monilipora* of Nicholson and Etheridge being in fact *Cladochonus*, their *Cladochonus* with which they contrast *Monilipora* is something quite different and in fact a genus that has no real existence. In so far as the character of being supported on little props is a part of the generic definition, that character probably does not exist, but is the product of a misconception by Milne-Edwards and Haime, and a misinterpretation of expressions used by De Koninck. In so far as the character of wall structure and internal structure is a part of the generic definition, the specimens showing those characters are probably not correctly referred to *C. Michelini* and are of unknown relationship. *Pyrgia* also is probably a synonym of *Cladochonus*, but if the specimens just mentioned actually belong to *C. Michelini*, which is the typical species of *Pyrgia*, then *Pyrgia* becomes once more a valid genus, for the structural characters shown by the Scotch specimens seem adequate to distinguish a genus even though that genus possesses, so far as known, the same habit of growth as true *Cladochonus*.

Authors writing of the genus *Monilipora* have generally laid

emphasis on a character ascribed to it also by Nicholson and Etheridge—the habit of these colonies of attaching themselves to crinoid colonies about which they form a ringlike growth. This is an interesting fact and one rather often to be observed, but its importance as a really generic character is open to doubt. It might be not even a specific character, or only a minor specific character. The importance ascribed to it would depend upon knowledge that we unfortunately do not possess, as to whether the selection of a crinoid column by the initial corallite was a matter of subjective or objective necessity or even of necessity at all. Just how one would classify a colony that had all the other characters of *Cladochonus*, but was attached to some spreading object instead of to a crinoid stem, is a problem not necessary to confront, though it might readily arise.

However important this character may be philosophically, its recognition as essential to the genus *Cladochonus* would multiply difficulties for the paleontologist, because very few of the specimens which he has to deal with afford any clue as to the manner in which the colony was attached or supported. These colonies, in fact, nearly always occur in a fragmentary condition, and it is rather the exception than the rule to find more than three or four corallites still joined together. The larger fragments are usually of two types, bushy growths attached to crinoid stems and elongated sprays whose attachment is not known. These two types are commonly found associated, however, and the constituent corallites of both have so much in common that it has rather generally been inferred that the spraylike forms were merely outgrowths of the bushy forms, though this relationship has rarely been observed. If we consider the possible vicissitudes of such colonies, both on the sea bottom and at the present day in process of collection, we would naturally expect that a large proportion of the sprays would be detached from their bases.

The bases and the sprays differ somewhat in their characters, and this also we would expect. The corallites of the basal group tend to be larger (?) and to grow in a more crowded and irregular manner, those of the sprays tend to be more slender and elongate (?) and to assume a more symmetrical balanced arrangement. Minor differ-

ences between the sprays and the basal tufts should not, at all events, militate strongly against referring them to the same species.

The fibrillated structure of the walls remains perhaps the most important distinctive character of the genus. This character, however, has been observed especially in very robust forms whose size would permit the walls to be much thickened and the structure to be coarse. One might foresee, however, that in smaller species the thickening of the walls might be so reduced and the whole construction so microscopic that the characteristic reticulate structure would be almost negligible in amount, though not perhaps in importance.

Of the species at present known from the Carboniferous rocks of North America and referred under the genera *Aulopora*, *Cladochonus*, and *Monilipora*, none perhaps properly belongs to *Aulopora*. To *Cladochonus* I would provisionally refer *C. Americanus* Weller, *A. amplexa* Rowley, *M. Beecheri* Grabau, *M. crassa* (as identified by Weller), *C. fragilis* Mather, *A. gracilis* Keyes, and *A. Longi* Rowley. To a different group, which I am at present not able to designate by name, would probably belong *A. Anna* Beede, *A. Prosseri* Beede, and *C. Bennetti* Beede. It is far from certain that these three species belong together, but none of them apparently belongs to *Cladochonus*. A third type appears to be represented by *A. geometrica*. Little can be seen of the internal structure of the type specimen, but if what can be seen is not misleading, *A. geometrica* is more intimately related to *Syringopora* than to *Aulopora*, and may be a colony of some species of *Syringopora* in an early stage, as for instance, *S. aculeata*.

A DISCUSSION OF CERTAIN GEOLOGIC FEATURES OF THE WASATCH MOUNTAINS

HYRUM SCHNEIDER
University of Utah

ABSTRACT

This paper discusses: (1) an 18-mile section of the Wasatch Front Range east of Salt Lake City. (*a*) The Wasatch fault is an initial fault-scarp modified by erosion and not a fault-line scarp. (*b*) The area is complexly folded and faulted. (*c*) Differences in the pre-Cambrian rocks at the north and south ends of the section are pointed out and the younger rocks are correlated with the rocks in the Cottonwood and Park City districts. (2) Rock Creek Canyon near Provo exposes an overturned anticline which probably has an important bearing on the structure of that section of the Wasatch Mountains. (3) Cache Valley, the depression between the Wasatch Front and Bear River ranges, is a down-faulted block and not a syncline as shown on geologic maps. (4) The folds and probably the thrust faults in the Wasatch Mountains were developed at the close of the Cretaceous or early Tertiary periods. The Wasatch and other major normal faults of the area were probably initiated near the middle of the Miocene, and the later movements have been along the old lines. (5) The conclusions of the writer regarding the east rim of the Great Basin substantially agree with conclusions regarding the western part of the Great Basin presented in a recent paper by Louderback.

INTRODUCTION

In northeastern Utah the Wasatch Mountains comprise two distinct parallel ranges separated from each other by Cache Valley. The eastern range has been called the "Bear River Range." The western range might be designated as the "Wasatch Front Range." South of Cache Valley the Bear River Range passes into the Bear River Plateau and loses its identity as a distinct range, whereas the Wasatch Front Range becomes more prominent, especially its west face along the Wasatch fault which extends roughly north and south, for a distance of about 150 miles from Collinston on the north to Mount Nebo on the south. Over forty years ago the region was mapped and the general features of its geology discussed by the geologists of the Survey of the Fortieth Parallel.[1] Since that pioneer work, contributions have been made from time to time, including

[1] *U.S. Geological Exploration of the Fortieth Parallel*, Vol. I, 1877; Vol. II, 1877; Vol. III, 1878.

some notable recent papers. Of these, Blackwelder's[1] paper deals more particularly with the northern part of the Wasatch Front Range; the work of Boutwell,[2] Hintze,[3] Butler,[4] J. J. Beeson,[5] and Calkins[6] deals with the central Wasatch Mountains, and Loughlin's[7] reconnaissance includes the southern part of the Wasatch Mountains. These contributions have added much to our information concerning the Wasatch Front Range, but there are still large areas known only in a general way and many problems, yet to be solved.

The present paper deals particularly with the area directly east of Salt Lake City, north of Big Cottonwood Canyon, and south of the town of Bountiful (Fig. 1). It involves a north-south section about 18 miles in length. In a more general way references are made to other sections of the region, including the origin of Cache Valley and the structure shown in Rock Canyon, near Provo. But only the more salient features will be discussed.

For his painstaking efforts in drawing the diagrams which accompany this paper, the writer desires to thank R. E. Marsell.

THE WASATCH FRONT EAST OF SALT LAKE CITY

Over fifty years ago a study of the geology of this region was begun by S. F. Emmons.[8] His observations were published in 1877. Since that time, so far as the writer knows, nothing has been published on this particular section.

[1] Eliot Blackwelder, "New Light on the Geology of the Wasatch Mountains, Utah," *Bull. Geol. Soc. Amer.*, Vol. XXI (1910), pp. 517–42.

[2] J. M. Boutwell, "Geology and Ore Deposits of the Park City District, Utah," *U.S. Geol. Surv., Prof. Paper 77* (1912).

[3] F. F. Hintze, Jr., "A Contribution to the Geology of the Wasatch Mountains, Utah," *Annals New York Acad. Sci.*, Vol. XXIII (1913), pp. 85–143.

[4] B. S. Butler and G. F. Loughlin, "A Reconnaissance of Cottonwood American Fork Mining Region," *U.S. Geol. Surv. Bull. 620* (1915), pp. 165–226; B. S. Butler, G. F. Loughlin, V. C. Heikes, and Others, "Wasatch Range," *U.S. Geol. Surv., Prof. Paper 111* (1920), pp. 216–334.

[5] J. J. Beeson, work done for Emma Consolidated Copper Co.

[6] F. C. Calkins, "Cottonwood American Fork Area," *U.S. Geol. Surv., Prof. Paper 111* (1920), pp. 229–54.

[7] G. F. Loughlin, "Reconnaissance in Southern Wasatch Mountains, Utah," *Jour. of Geol.*, Vol. XXI (1913), pp. 436–52.

[8] S. F. Emmons, *U.S. Geol. Exploration of the Fortieth Parallel*, Vol. II (1877), pp. 368–77.

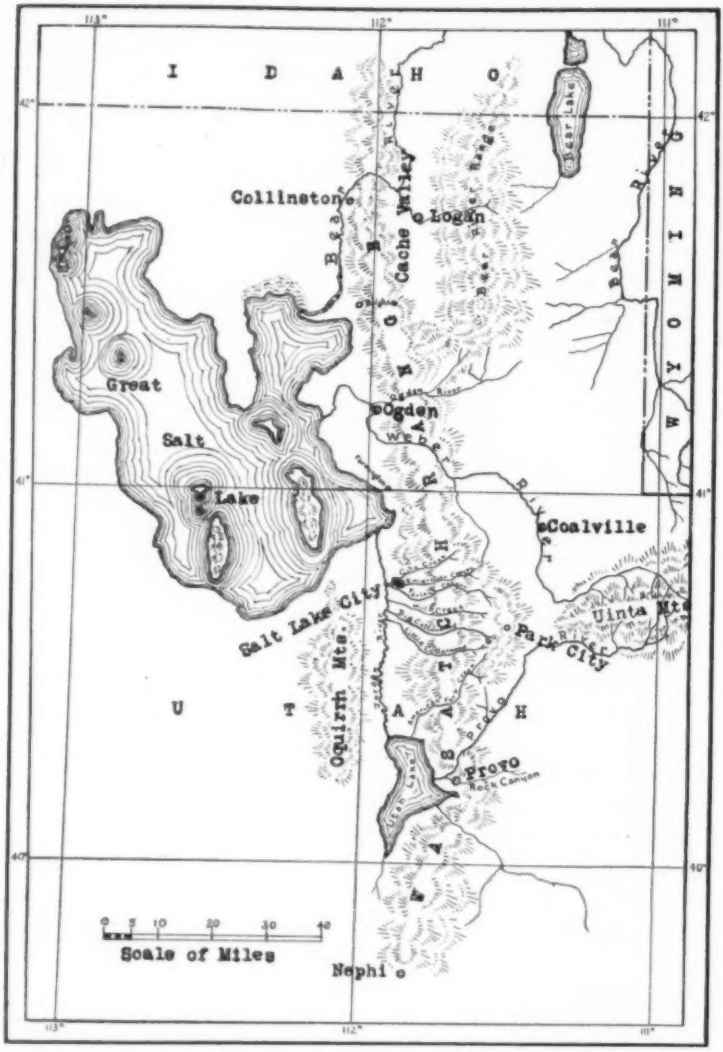

FIG. 1.—Map showing the location of the area under discussion, in relation to the Wasatch Mountains as a whole.

In what is here called the "Wasatch Front," the most conspicuous physiographic feature is the abrupt escarpment that separates the mountain mass on the east from Salt Lake Valley on the west. This mountain block, as seen from one of its peaks, appears to be a dissected plateau. The relatively short streams that flow westward into Salt Lake Valley have cut deep canyons which, particularly near their mouths, are roughly parallel to the strike of the rock formations. The streams appear to be consequent streams although they may be obsequent. Since a discussion of the physiographic history of this earth block would be in itself sufficient for a paper, it will not be attempted here. However, the west-facing escarpment, because of its prominence and relation to other problems of the region, calls for further discussion.

As to the nature of this escarpment there seems to be some difference of opinion. The writer, in agreement with many others, considers it an initial fault-scarp modified by erosion. On page 369 of the *Textbook of Geology*, by Pirsson and Schuchert (1920 ed.), we find the following statement:

> The east slope of the Sierra Nevada, the west slope of the Wasatch, and the steep faces of the intervening north and south ranges of the Great Basin as previously discussed are held to represent more or less eroded fault-line scarps.

The writer's students who use this book as a text invariably desire to know why it calls the west slope of the Wasatch a fault-line scarp. The question is a pertinent one because the evidence seen and discussed in our field trips indicates an initial scarp rather than a fault-line scarp. The present difference in elevation between the floor of Salt Lake Valley and the crest of the escarpment is between 3,000 and 4,500 feet. The valley floor lies below detrital material of unknown depth. Wells driven to a depth of over 2,000 feet have not reached the bottom of the valley-fill. This means, if the west slope of the Wasatch is a fault-line scarp, that there must have been, before the deposition of the valley-fill began, an erosion scarp of over 6,000 feet. Naturally one asks what were the agents of erosion? What rock formations were removed? Why have conditions been reversed frcm erosion to sedimentation? Unless these questions can be satisfactorily answered, some other theory of origin must be considered.

Four years ago the removal of Lake Bonneville deposits from along the base of the escarpment a little north of Salt Lake City exposed slickensided striated surfaces of Paleozoic limestone. The fault surface thus exposed is shown in Figure 2. At this point the fault strikes northwestward, and dips 72° westward. How long this fault surface may have been protected by Lake Bonneville waters, or even earlier lake waters and detrital material, is difficult to estimate. That it is a surface in the inner part of the Wasatch fault zone and that it represents the direction and

FIG. 2.—A slickensided surface, in the Wasatch fault zone, recently uncovered by the removal of Lake Bonneville sediments.

angle of dip of the Wasatch fault at this locality, is quite certain. As shown in Figure 3, we find directly above, on the crest of the escarpment, a considerable thickness of Wasatch conglomerate lying unconformably on the older rocks. Before faulting, this conglomerate must have extended much farther west than the present escarpment and, therefore, must have been cut off by the Wasatch fault. If this is true, the down-faulted portion is now buried deep beneath the valley-fill. This fact proves, in the opinion of the writer, that the present west slope of the Wasatch is an initial fault-scarp modified by erosion and not a fault-line scarp.

STRUCTURE

The Wasatch fault and the deep canyons cut by the westward-flowing streams have exposed to view the structure of the rocks that compose the mountain block east of Salt Lake City. As shown in Figure 2, the major structure is a synclinorium with its major axis about halfway between two exposures of earlier pre-Cambrian rocks. Near the center of the major synclinal structure there is a pronounced anticline between two synclines. The strike of the axes of these folds is about N. 45° E., and they pitch steeply to the eastward so that, in following them eastward along their axes, they soon lose their identity. On the west they have been cut off by the Wasatch fault, a condition that renders their westward extent undeterminable. Since no evidence of them occurs in the Oquirrh Range on the west side of the valley, they are probably doubly pitching and may never

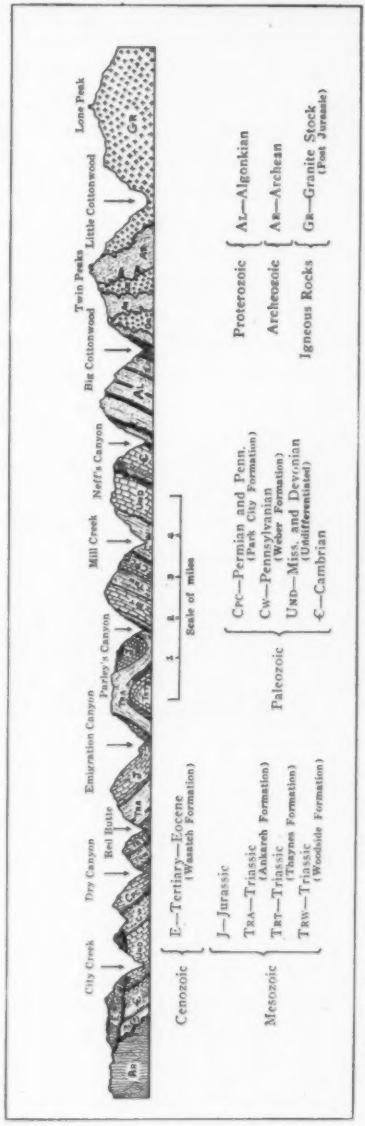

FIG. 3.—Diagrammatic geologic structure section and profile of west front of Wasatch Mountains near Salt Lake City, showing the structure, stratigraphy, and location of the various canyons cut by the streams that drain into Salt Lake Valley.

have extended far west of the present Wasatch scarp. Besides the folds shown in Figure 3, there are several minor folds too small to be shown in the drawing. The minor folds occur mostly in the weaker rocks, notably in the shaly Jurassic limestone. A minor fold of some consequence is developed in the Park City formation near the mouth of Mill Creek Canyon. On the ridge between Emigration and Red Butte canyons, about 1½ miles up from the mouth of Red Butte Canyon, there is a pronounced dragfold involving the Ankareh and Jurassic formations.

In the central part of the section the regional strike is about N. 45° E. However, across and along the strike of the strata, there is considerable variation in strike and dip. At the south end of the section the regional strike changes from northeastward to southeastward, whereas at the north end of the section the regional strike becomes more nearly north and south. It seems that to a considerable extent, the older and relatively stronger pre-Cambrian rock blocks determined the trend of the folds.

The area is not only much folded but also complexly faulted. Besides the Wasatch fault, which produced the scarp along the Wasatch Front, there are numerous minor faults. Like the Wasatch fault, the minor faults, in so far as the writer has determined them, are normal faults, with a displacement varying from a few to several hundred feet. One of the most complexly faulted blocks in the section is the one between Dry and Red Butte canyons. Just south of Emigration Canyon there is a fault of considerable displacement that offsets the Ankareh formation. Near the mouth of Neff's Canyon a similar fault brings limestone into contact with quartzite. Both of these faults cut the Wasatch scarp at a slight angle and strike a little east of south, with the down-throw to the east.

North of Salt Lake City below Ensign Peak, the Park City and older formations are exposed along the base of the Wasatch scarp. The upper part of the scarp is in Wasatch conglomerate, which unconformably overlies the older rocks. In their relation to rocks of the same age, shown in the structure diagram, Figure 3, the Paleozoic rocks, exposed below Ensign Peak, are 2 miles north of where they should be. To account for the occurrence of these rocks far from their normal position and striking toward Archean

rocks is one of the problems of this district. Faulting is the only explanation that has thus far occurred to the writer. If a fault has placed these rocks in their present position, it must be an ancient one much older than the Wasatch fault, and older, in fact, than the Wasatch conglomerate. If such a fault exists, the Wasatch conglomerate was deposited across its trace. Moreover, to account for a horizontal shift in outcrops of over 2 miles, the fault must have a pronounced horizontal component. The writer feels that the problem is not completely solved. Its solution is made more difficult by the cover of Wasatch conglomerate and Quaternary sediments, which separate this outcrop from the other older rocks.

There are other structural problems in this district that can be solved only in connection with careful and detailed mapping.

STRATIGRAPHY

The geologic map of this area made by the Survey of the Fortieth Parallel shows the following formations: Archean, Cambrian, Ute, Ogden, Nevada, Sub-Carboniferous, Lower Coal-Measures, Weber quartzite, Upper Coal-Measures, Permo-Carboniferous, Red Beds, Jurassic, and Vermillion Creek. The writer has correlated the rock formations of this section with the rocks of the Park City and Cottonwood districts. Their age, formation-name, and stratigraphic relation are shown in Figure 3; also in Table I. The correlation is not based on detailed fossil evidence but largely on lithologic characteristics and stratigraphic position. A detailed study of the fossil record may call for some revision. However, in connection with the physical characteristics and stratigraphic position, the writer has found and studied enough fossils to make him fairly confident that any revision made for this section will probably apply also to the Park City and Cottonwood districts.

It is beyond the scope of this paper to enter into a detailed discussion of the stratigraphy. Nevertheless, certain outstanding features need further explanation.

The rocks shown as Archean between Big and Little Cottonwood canyons are schists and gneisses of varied composition and texture, which appear to be, for the most part, metamorphosed sediments. The Archeozoic rocks north of City Creek Canyon are also schists

and gneisses, but they differ considerably in composition and possibly in intensity of metamorphism from the Cottonwood schists and gnesisses. The northern schists and gneisses are cut by

TABLE I

U. S. Survey of the Fortieth Parallel, Map III		Section Figure 2 of This Paper	
Age	Formation	Formation	Age
Eocene	Vermillion Creek	Wasatch conglomerate	Eocene
			Unconformity
Jurassic		Twin Creek	Jurassic
Triassic	Red Beds	Ankareh	Triassic
Carboniferous	Premo-Carboniferous	Thaynes	
		Woodside	
			Disconformity
	Upper-Coal-Measures	Park City	Penn & Permian
			Disconformity
	Weber quartzite	Weber quartzite	Pennsylvanian
			Unconformity
	Lower Coal-Measures	Limestone	Mississippian
	Sub-Carboniferous		
Devonian	Nevada	Limestone	Devonian
			Unconformity
	Ogden	Sandstone	Cambrian
Silurian	Ute	Limestone	
Cambrian	Shale	Shale	
	Slates and quartzite	Quartzite	
			Unconformity
		Slates and quartzite	Algonkian
			Unconformity
Archean	Schists and gneisses Granite	Schists and gneisses	Archean

numerous pegmatite dikes which are notably absent south of Big Cottonwood Canyon. These differences suggest that the Cottonwood schists and gneisses may be early Proterozoic in age instead of Archeozoic.

Another notable difference between the north limb and the south limb of the synclinorium is the difference in the thickness of the Algonkian rocks. North of City Creek Canyon there are no slates between the known Cambrian shales and the Archean complex. The base of the sedimentary series is a quartzite pebble conglomerate directly in contact with the Archean complex. The writer has not found any convincing evidence of an unconformity between the one at the top of the Archeozoic rocks and the Cambrian shale. Moreover, the total thickness of the quartzite and conglomerate between the known Cambrian shale and the Archean rocks is only a little greater than the thickness of Cambrian quartzite and conglomerate south of Neff's Canyon. This fact suggests the complete absence at the north end of the section of the thick Algonkian quartzite slate series exposed between Big Cottonwood and Neff's canyons. The entire absence, or greatly reduced thickness, of the Algonkian rocks at the north end of the section, as compared with the south end, might be due either to difference in erosion or to difference in deposition, or perhaps to both. Considering the slight distance involved, the case is unusual, and a problem for further investigation.

The contact between the Devonian and the Cambrian rocks, north of Neff's Canyon, is marked by a poorly exposed basal conglomerate and a slight, angular discordance. About 140 feet below the top of the Cambrian system there are approximately 200–250 feet of cream to buff or brown cliff-forming sandstone. Calkins[1] does not mention any sandstone near the top of the Cambrian in the Cottonwood district. Its presence in Neff's Canyon and its absence only a few miles southeast in the Cottonwood district may be accounted for by difference in erosion in connection with the unconformity at the base of the Devonian. It was probably this sandy member at the top of the Cambrian, and just

[1] F. C. Calkins, "Cottonwood American Fork Area," *U.S. Geol. Surv., Prof. Paper 111* (1920), p. 236.

below the Devonian, that the Fortieth Parallel Survey mapped as the Ogden quartzite.

The Weber formation, typically a quartzite, is true to type in Mill Creek Canyon; but between Dry Canyon and City Creek where it is exposed it is a cream-colored, friable, calcareous sandstone, with only here and there lentils of quartzite; and here, instead of forming cliffs, it forms an erosion depression.

In Mill Creek Canyon there is evidence of a disconformity between the Weber and Park City formations, and similar evidence between the Park City and Woodside formations in Dry Canyon. As in the Park City district, the Woodside appears to be continental rather than marine. It is more sandy and more calcareous than in the Park City district, but is not so deep red in color.

The Ankareh in this section is dominantly a sandstone with shaly members. Excepting the shaly members, the formation is lighter red in color than the Ankareh of the Park City district, where it is dominantly a shale.

In the Park City district the Nugget formation overlies the Ankareh. The Nugget is a coarse-grained, white- to cream-colored sandstone or grit. Its characteristics suggest continental origin. In the Salt Lake City section the rock directly overlying the Ankareh is a drab to gray shaly limestone of marine origin. It is highly jointed, and in places the joint planes may easily be confused with bedding planes. It is probably the equivalent of the Twin Creek formation of southwestern Wyoming and southern Idaho.

STRUCTURE IN ROCK CREEK CANYON

In the Wasatch Front Range, just east and a little north of Provo, an important structural feature that otherwise might remain unknown is exposed in a canyon cut by Rock Creek. As we look at the Wasatch Front on either side of Rock Creek Canyon, from the railroad, the State Highway, or even from a few rods outside the canyon's mouth, we get the impression that the rocks are nearly horizontal with only a slight dip into the mountain; that the Wasatch Range here is truly a fault block, tipped gently eastward; or that it is a part of the east limb of a gentle anticline. Closer study of the range north and south of Rock Creek strengthens

that impression. But a study of the structure as exposed in Rock Creek Canyon leads to an entirely different conclusion as to the structure of this part of the Wasatch Range. S. F. Emmons recognizes an unusual structure here. He says:

> As the face of the hills on either side of Rock Canon shows nearly horizontal lines of stratification, like that of Timpanogos Peak, the observer, on entering the cañon, and finding in its bottom clay-slates and quartzites standing perpendicularly, and even with a slight westerly dip, is at first led to believe that he has here a series of rocks entirely unconformable to the overlying strata of limestone. But ascending the cañon the beds are found, without showing any distinct break, to dip with an ever diminishing angle to the eastward, and soon beds evidently conformable with the first observed can be traced continuously along the cañon-wall, curving upward and westward from a dip of over 60° east in the cañon-bottom to an almost horizontal position high up on the spurs, and at times even with a slight inclination westward. There is here therefore a sharp S-shaped fold, the lower half of which is concealed beneath the surface, while the western front of the upper half has been broken down in a fault.[1]

Emmons recognized, in part at least, the nature of the fold in Rock Canyon; but he did not seem to have been aware of its magnitude nor of its bearing on other structural problems of the eastern part of the Great Basin.

The writer first saw Rock Canyon in the spring of 1916. At that time he knew nothing of its structure. On entering the canyon he was greatly surprised to see in its bottom rocks dipping westward at an angle of from 65° to 75°, while above, on the canyon wall, hundreds of feet of strata dip eastward at a low angle. One certainly gets the impression here of a pronounced angular unconformity, and this impression remains until the observer has ascended the canyon well out of the quartzite into limestone. At this point he may plainly see, as shown in the photograph (Fig. 4), limestone beds that make a rather sharp turn from a steep westward to an eastward dip. Not until then does he begin to realize that the bottom of Rock Canyon follows closely along the axis of a strongly overturned anticline. The brittle quartzites at the mouth of the canyon are considerably shattered along the axis of the fold—a condition that makes it difficult to recognize the true nature of the structure until the more flexible limestone beds are seen making the

[1] *U.S. Geol. Exploration of the Fortieth Parallel*, Vol. II (1877), pp. 345–46.

sharp turn without a break. After observing the fold in the limestone and then returning to the quartzite, the observer can follow the quartzite strata up the steeply westward dipping limb through the shattered zone, along the axis of the fold, to the upper nearly horizontal limb. Figure 5 shows the nature of the fold and how it has been cut off by the Wasatch fault. The original fault-scarp has been considerably modified by erosion but, as indicated by an uneroded scarp that cuts across a post-Bonneville alluvial fan at the mouth of Rock Canyon, there has been a recent movement along the Wasatch fault. That this relatively recent movement was more or less general along the Wasatch Range is indicated by similar scarps in post-Bonneville alluvium between Big and Little Cottonwood creeks south of Salt Lake City, and also near Beck's Hot Springs north of Salt Lake City.

FIG. 4.—View looking north in Rock Canyon, east of Provo. The sharply bent limestone beds show the position of the axis of an overturned anticline.

S. F. Emmons seems to have considered the fold in Rock Canyon more or less local and a result of faulting.[1] The writer feels that the fold is not necessarily local because it is not exposed along the Wasatch Front. The fold involves a great thickness of strata ranging in age from pre-Cambrian to late Paleozoic. Its north to south extent is somewhat difficult to determine. Where the axis of the fold lies beneath the base of the Wasatch scarp, and below the bottom of even the larger canyons, as seems to be the case in Provo Canyon, the observer is not aware of the existence of an overturned anticline and is led to interpret the structure as quite

[1] S. F. Emmons, *op. cit.*, p. 345.

different from what it actually is. The magnitude of the fold, as shown in Rock Canyon, and the fact that if its axis were just a little below, instead of a little above, the bottom of the canyon, its existence even in Rock Canyon would be unobservable, leads the writer to infer that the overturned anticline probably has a considerable north-south extent and has played an important rôle in determining the structure of this section. The thickness of the strata involved, and the way in which the fold is overturned to the east, suggest a strong pressure from the west. It is further probable that the folding in the Basin ranges of Utah took place during the orogenic epoch that caused the folding in the Wasatch ranges.

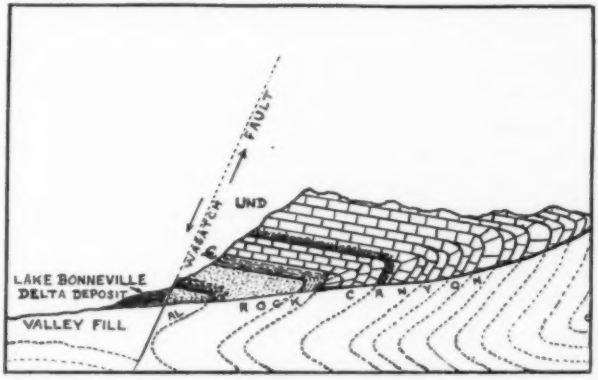

FIG. 5.—Diagram of the overturned anticline in Rock Canyon

As indicated at the beginning of the last paragraph, S. F. Emmons connected the Rock Canyon fold with Wasatch faulting. The writer believes that the folding in the Wasatch and northeastern Basin ranges was separated by a considerable time interval from the crustal disturbance that initiated the Wasatch and similar Great Basin faults. The time of folding and faulting will be discussed in another part of this paper.

CACHE VALLEY

The depression that separates the Bear River Range from the Wasatch Front Range is known as Cache Valley. It is a north-south valley with a total length of about 40 miles and a width of

from 12 to 15 miles. A little less than three-fourths of the valley is in Utah, the remainder being in Idaho.

This level, fertile tract of land between two mountain ranges attracts attention. The physiographer and the geologist desire to know its origin. Map III, of the atlas that accompanies the reports of the United States Exploration of the Fortieth Parallel, shows Cache Valley as a synclinal valley. The map that accompanies the *United States Geological Survey Professional Paper 111* also shows Cache Valley as a syncline. The writer[1] has for some time considered Cache Valley a down-faulted block and not a down-fold. If there is a syncline in Cache Valley the structure of the rocks visible in the west-facing scarp of the Bear River Range, directly east of Cache Valley, does not indicate it. In fact, a study of the structure in Logan Canyon suggests that the down-faulted block is anticlinal rather than synclinal. In ascending Logan Canyon, one passes from older to younger rocks. Moreover, the dip is eastward. At the mouth of Logan Canyon the rocks dip 30°, but the dip decreases as one approaches the axis of a syncline, 4 or 5 miles up the canyon. To the east of the syncline the strata seem to pass into a gentle anticline. In the down-faulted block in Cache Valley probably the same type of folding exists as that which is now observable in the up-thrown block in Logan Canyon east of Cache Valley. If the foregoing reasoning is correct, Cache Valley, instead of being due to a down-fold, as indicated by the geologic maps, may actually be a down-faulted anticline. Because of the deep valley-fill, we may never be able to determine positively the structure of the older rocks beneath the Quaternary and Recent sediments; but even so, the available evidence strongly favors the theory of down-faulting rather than down-folding.

Peterson[2] has recently shown that there are north-south faults along the east and west sides of Cache Valley and also an east-west fault across the south end. Wells driven for oil have reached

[1] Hyrum Schneider, "Possibilities of Oil and Gas in Salt Lake and Cache Valleys," *Trans. of the Utah Acad. of Sci.*, Vol. II (1918–21), p. 39; "General Geology of Utah," *Bull. of the Univ. of Utah*, Vol. X, No. 11 (1919), p. 17.

[2] William Peterson, "A Report on Cache Valley," *Trans. of the Utah Acad. of Sci.* (1922), not yet published.

an old rock surface beneath 1,600 to 1,800 feet of valley-fill. A part of the valley-fill is lake and bog deposits.

The west face of the Bear River Range rises abruptly from 2,500 to 4,500 feet above Cache Valley. Its west-facing scarp is comparable with the Wasatch fault-scarp along the west side of the Wasatch Front Range. It is similar also to the fault-scarps of some of the Basin ranges. There is considerable evidence that it is an initial fault-scarp greatly modified by erosion. There is also evidence that it is a fault-line scarp.

Dr. Eliot Blackwelder[1] has found a fault near the west base of the Bear River Range that is older than the present topography. He also believes that considerable of the so-called "valley-fill" is poorly consolidated Tertiary sediments, similar to stratified volcanic ash and fresh-water limestone that now occurs on parts of the west rim of Cache Valley. It is his opinion that a fault of large displacement, along the east side of Cache Valley, brought poorly consolidated Tertiary sediments in contact with the older, more resistant rocks of the Bear River Range and that during the present erosion cycle the weak Tertiary sediments have been eroded away. This view would make the west face of the Bear River Range a fault-line scarp and Cache Valley an erosion valley, in part blocked out by an old fault.

After discussing the origin of Cache Valley with Dr. Blackwelder, the writer again visited the area and examined some of the field evidence. He has also discussed with Professor William Peterson and Reed Bailey, of the Utah Agricultural College, their views regarding the origin of Cache Valley. Both are convinced, from field work which they have done, that Cache Valley is due primarily to faulting.

The evidence of a fault in the Bear River Range older than the present topography is conclusive. However, it is also probable that there are parallel faults, nearer the valley, that are in part responsible for the difference in elevation between the valley and the mountains.

The writer is convinced that there has been faulting along the west side of Cache Valley. Some of the displacement has been

[1] Personal communication.

recent enough to be in part, at least, responsible for the present difference in elevation between the valley floor and the west rim.

If the present difference in elevation, between the valley and the bounding mountains, is due entirely to erosion, either the greater part of the material must have been carried out of the area along present drainage lines or there has been a change in drainage. The physiographic evidence is against a change in drainage during the present erosion cycle. Some of the sediments might have been removed, by way of Red Rock Pass, at the north end of the valley. The greater portion could have been carried out of the valley, only through the Bear River gap, in the Wasatch Front Range. When we consider the size of Cache Valley, in relation to the Bear River gap, that does not seem probable.

If we accept Dr. Blackwelder's interpretation of the Cache Valley well log, and assign 1,000 feet of the poorly consolidated sediments, in the bottom of the valley, to the Tertiary, we still have, at least, 250 feet of Bonneville and post-Bonneville deposits, which means that the bottom of indisputable valley-fill is 150 feet or more below the lowest point in the valley rim. This point is at the entrance of the narrow gap, cut entirely in Paleozoic rocks, through which Bear River crosses the Wasatch Front Range. The fact that the lowest point in the valley rim is in Paleozoic rocks and is higher than the bottom of valley-fill suggests that the present valley depression is, at least in part, due directly to faulting.

Although there is a difference of opinion as to the relative importance of faulting and erosion in the development of Cache Valley, it must be admitted that faulting, either directly or indirectly, has played an important part. That Cache Valley is not a synclinal valley can be proved beyond question.

EPOCHS OF FOLDING AND FAULTING

In considering the geologic history of the Wasatch Mountains one finds evidence of more than one orogenic disturbance. The first epoch of disturbance was that of folding, which gave birth to the Wasatch and other Rocky Mountain ranges. Along with the folding, there seems to have been in the Wasatch Mountains some thrust-faulting. The age of the folds can be definitely fixed as late

Cretaceous or early Tertiary, because the Cretaceous rocks are involved in the folding, while the Wasatch conglomerate (Eocene) is nearly horizontal and rests on the truncated edges of the older folded rocks.

The time of uplifting and faulting that produced the faults along the Wasatch Front and Bear River ranges cannot be so definitely determined. Grabau[1] infers that the development of a great arch, between the Wasatch and the Sierra Nevada mountains, and its collapse into a series of north-south fault blocks, which now form the Basin ranges, took place at the time of the folding in the Rocky Mountains. The evidence in the Wasatch Mountains does not bear out this inference. The Wasatch fault was almost certainly initiated at the same time as were the Basin Range faults. The displacement along the Wasatch fault, now a pronounced topographic feature, took place long after the folding in the Wasatch Mountains. This is indicated by the relation of the Wasatch fault to the Wasatch conglomerate and by the relation of the Wasatch conglomerate to the epoch of folding. As shown in Figure 3, the Wasatch conglomerate was deposited on the truncated edges of the folded rocks and was later cut off by the Wasatch fault. After the epoch of folding, and before the Wasatch conglomerate was deposited, there was partial peneplanation. Some time after the deposition of the conglomerate, the displacement that now marks the eastern rim of the Great Basin was begun. The exact time is somewhat difficult to determine if only the Wasatch Mountains are considered, but it can be fixed with more certainty if studied in its relation to the disturbances in the entire plateau province.

A study of the middle Tertiary disturbance in Western North America has led the writer[2] to conclude that the major topographic features of the Great Basin had their beginning in connection with the extensive mountain-making epoch which began along the Pacific Coast near the middle of Miocene time. Along the lines then blocked out there have undoubtedly been later movements. The

[1] A. W. Grabau, *A Textbook of Geology; Part II, Historical Geology* (1921), pp. 784–85.

[2] Hyrum Schneider, "Mid-Tertiary Deformation of Western North America," *Trans. of the Utah Acad. of Sci.*, Vol. II (1918–21), pp. 159–60.

displacement along the Wasatch fault cannot be less than 6,000, and may be as much as 10,000 feet. Along the west face of the Bear River Range the displacement is probably almost as great. The total displacement represents a series of movements. As indicated in another part of this paper, there is evidence of very recent movement along the Wasatch fault.

Huntington and Goldthwait[1] speak of faulting and flexing in Miocene time along the Hurricane fault near Toquerville, Utah. The Hurricane, Wasatch, and other major faults in the eastern part of the Great Basin probably had their beginning at the same time. According to the available evidence, this seems to have been near the middle of the Miocene. The plateau country and the Great Basin seem to have had their beginning as physiographic provinces in connection with the Middle Miocene uplift. Along the lines thus established, later adjustments have been made.

GREAT BASIN RANGES

The mountain ranges in the Great Basin present a physiographic problem whose solution is not easy. Many of these ranges are discontinuous, disconnected, more or less isolated, and half buried in their own detrital material. In some cases they rise abruptly out of the alkali desert like a rocky island out of a lake.

Opposing the theory of differential erosion, and especially that of wind erosion, Louderback[2] in a recent paper mentions various explanations that have been offered to account for the present physiography of the Great Basin. He discusses, in particular, faulting as a dominant factor. From a study of the Sierra Nevada and adjacent Basin ranges he concludes that for this part of the Great Basin block-faulting dominates the physiographic development. He thinks that there has not been post-faulting peneplanation; and that the east scarp of the Sierra Nevada and the scarps in the adjacent Basin ranges are initial fault-scarps modified by erosion, and not fault-line scarps developed by wind or any other agent of erosion. He presents evidence also of relatively

[1] "The Hurricane Fault in the Toquerville District, Utah," *Harv. Col. Mus. Comp. Zoöl., Bull. 42* (1903–5), pp. 218–23.

[2] George D. Louderback, "Basin Range Structure in the Great Basin," *Univ. of Cal. Publ. Bull. of Dept. Geol. Sci.*, Vol. XIV, No. 10 (1923), pp. 329–76.

recent movements along some of the old fault lines. Louderback's conclusions for the western part of the Great Basin are essentially in accord with the conclusions of the writer regarding the east rim of the Great Basin.

While the writer believes that faulting has played an important part in the development of the unique Great Basin topography, he also believes that the structure of the Basin ranges is more complex than is suggested in textbook diagrams, such as the one shown on page 387 of *Physiography*, by Salisbury (1919 ed.). Moreover, a structure so simple for all the individual Basin ranges is not in accord with Gilbert's[1] original structure diagrams.

The diagrams in other textbooks give students the impression that an arch of nearly horizontal sedimentary rocks extended from the Wasatch to the Sierra Nevada mountains, and that the individual Basin ranges are tilted fault blocks of this broken arch, with the dip of the strata in the individual ranges in the same direction. If an arch ever extended from the Wasatch to the Sierrra Nevada mountains it was not a simple arch, of nearly horizontal rocks, but an uplift arch of an earth-block already complex in structure. This is shown by the complexity of the rocks and by the structure in the Wasatch Mountains as well as in some of the ranges in the northeastern part of the Great Basin.

Nearly parallel north-south normal faults may explain the existence of relatively elevated, comparatively narrow, earth blocks as we see them in the Basin ranges, but they do not explain their abrupt termination. As already stated in this paper, an east-west fault marks the south end of Cache Valley. Possibly east-west faults have something to do with the abrupt termination of some of the Basin ranges.

SUMMARY

The major structural feature in the Wasatch Front Range in the section east of Salt Lake City is a synclinorium with its major axis about halfway between two exposures of pre-Cambrian rocks. The folds pitch steeply northeastward, and the strike changes as one approaches the pre-Cambrian rocks on either limb. These

[1] G. K. Gilbert, *U.S. Geographical Survey West of the Hundredth Meridian* (*Wheeler Survey*), Vol. III (1875), pp. 21–42.

facts indicate that the old rock-blocks have determined the trend of the folding. The Wasatch fault, with a displacement of not less than 6,000 feet and possibly as much as 10,000 feet, has cut off the folds on the west. Besides the Wasatch fault there are many minor, normal faults. No reverse faults have been noted in this section.

The rocks range in age from Archeozoic to Jurassic. In this section, as in the Cottonwood district, the Ordovician and Silurian systems are not represented.

The rocks in the Wasatch Mountains east of Provo appear to be nearly horizontal or dipping eastward at a low angle. Actually, the structure is not so simple as it appears. Rock Canyon has exposed a strongly overturned anticline, which involves the whole stratigraphic section and indicates strong pressure from the west. Outside of Rock Canyon the observer sees only one limb of the anticline, and this limb has been cut off by the Wasatch fault. Seen from the west, this section of the Wasatch Range has thus the appearance of a simple uniclinal fault-block.

Wells driven in the valley and the structure of the rocks in the Bear River Range show that the depression between the Wasatch Front and Bear River ranges known as Cache Valley is not due to folding, but to faulting and erosion.

The west-facing scarp of the Wasatch Front Range is an initial fault-scarp modified by erosion, and not a fault-line scarp. The displacement is not less than 6,000 and possibly as much as 10,000 feet. The displacement probably began near Middle Miocene time. The latest movement is so recent that scarps formed in alluvium remain practically unaffected by erosion.

The crustal disturbance that gave birth to the Wasatch Front and Bear River Range faults produced also the Great Basin as a physiographic province. And at least some of the mountain ranges in the northeastern part of the Great Basin are fault-blocks with initial fault-scarps modified by erosion, rather than fault-line scarps.

STRATIGRAPHY OF THE KIMMSWICK LIMESTONE OF MISSOURI AND ILLINOIS

JOHN H. BRADLEY, JR.
University of Chicago

ABSTRACT

In this paper the general results of the writer's study of the large fauna of the Kimmswick limestone are presented. The description of species is to be published elsewhere. The study has demonstrated the marked faunal homogeneity of the formation vertically as well as horizontally, and from different types of evidence establishes the age of the Kimmswick as early Trenton rather than late Black River. Although essential contemporaneity is postulated for the Kimmswick and the Prosser of Minnesota, certain faunal differences strongly suggest a barrier between the northern and southern Mississippi Valley in early Trenton times. Evidence is presented to show that part of the Kimmswick fauna reached the lower Mississippi Valley by way of the Appalachian Valley, while another faunule seems to have entered from the west.

INTRODUCTION

The Kimmswick limestone was first[1] recognized as a distinct lithologic and faunal unit in the geological succession of southeastern Missouri, by E. O. Ulrich, who introduced the formational name in 1904[2] to apply to the "more or less crystalline limestone being quarried at Graysboro, Cape Girardeau, Glen Park, Kimmswick and other localities in southeastern Missouri." Lithologically distinct and homogeneous throughout its entire vertical and areal distribution, the Kimmswick limestone is easily distinguished from the subjacent Plattin limestone, which is everywhere fine grained, and the thin bed of Fernvale limestone which in most localities occurs

[1] While Ulrich was the first to demonstrate the unity of the formation in question on a faunal as well as a lithological basis, and his term has been generally accepted, it should be mentioned that Broadhead (*Geol. Surv. of State of Missouri* [1855–71], p. 49) recognized the lithological uniqueness of the pure, light-colored, crystalline limestone, now known by Ulrich's term, Kimmswick, and called this formation the Charette limestone from its outcrops in Warren County, Missouri. The formation is 34 feet thick in this locality, and thins rapidly westward, being entirely absent a short distance west of the eastern boundary of Callaway County. Broadhead's term has been quite correctly superseded by Ulrich's, which is based upon the formation as exposed in Jefferson County, Missouri, where its faunal and stratigraphic relationships can best be studied.

[2] *Missouri Bureau Geology and Mines*, Vol. II (2d series), p. 111.

directly above. The Plattin limestone carries a fauna of Black River age, and is separated from the Kimmswick by a disconformity. The Fernvale bed above the Kimmswick is likewise in disconformable contact.

USAGE OF THE TERM KIMMSWICK

Since the introduction of the term Kimmswick, Missouri geologists have been disposed to include in that formation all of the pure, distinctly crystalline limestone of Mohawkian age between the lower darker and extremely fine-grained limestone, which they call Plattin, and the overlying Fernvale limestone. This broad usage was employed by E. B. Branson in 1918.[1]

Previous to this, however, in a classification of Lower and Middle Ordovician strata in Missouri, C. R. Keyes[2] used the term Bryant limestone for beds in the northeastern part of Lincoln County and northward into Pike County which Branson has included in the Plattin. For the massive buff, abundantly fossiliferous limestone above, Keyes used the term McCune limestone. He states that the best exposures of the formation are on Peno Creek, near McCune station, 12 miles west of Louisiana, in Pike County, Missouri. This formation was called Kimmswick by Branson in the same locality.

According to Branson, the McCune limestone of northeastern Missouri and the Kimmswick limestone of southeastern Missouri are equivalent, although this view is not held by Ulrich, who prefers to use the term in a more restricted sense and considers the McCune a younger formation.[3] All of these formations have been loosely referred to by Worthen and others as Trenton, and the Kimmswick is known locally as the Receptaculite limestone, because of the abundance of *Receptaculites oweni* Hall in beds of the upper part of the formation.

AREAL EXTENT OF THE KIMMSWICK LIMESTONE

The type exposures of the Kimmswick are in Jefferson County, Missouri, close to the Mississippi River, in the vicinity of the village

[1] "Geology of Missouri," *University of Missouri Bulletin*, Vol. XIX, No. 15, pp. 53–54.

[2] C. R. Keyes, *Proc. Iowa Acad. Sci.*, Vol. V (1898), p. 61.

[3] "Revision of the Paleozoic Systems," *Bull. Geol. Soc. America*, Vol. XXII, No. 3 (1911), Pl. XXVII.

of Kimmswick, about 20 miles south of St. Louis, and thence southward in a narrow belt along the river to the vicinity of Riverside, 8 miles distant. Outcrops continue southeastwardly in a sinuous belt which is usually less than 5 miles wide, and always within 10 miles of the river, across Ste. Genevieve, Perry, and Cape Girardeau counties. In the last three counties only the upper horizons of the formation are exposed. The most southerly exposures in Missouri are in Scott County south of Graysboro. Across the river in Illinois the Kimmswick limestone is brought to the surface on an anticline along the river at Valmeyer in Monroe County, nearly opposite Glen Park, Missouri, and is known as far south as the vicinity of Thebes, Alexander County, Illinois, which is nearly opposite Graysboro, Missouri. Southward from this locality the Kimmswick limestone has not been mapped.

Northward and westward from the type locality in Jefferson County, Missouri, interpreting the formation broadly with Branson and Foerste,[1] the Kimmswick limestone can be followed into Franklin and St. Louis counties. In the latter, near Minke, about 20 miles southwest of St. Louis, the formation is well exposed in a quarry of the Glencoe Lime and Cement Company. Northward, outcrops are known in Warren County as far west as Callaway County, but also to the east in St. Charles County whence the formation has been traced through Lincoln, Pike, and Ralls counties.[2] In the last three counties the Kimmswick is near the Mississippi River as in southeastern Missouri, and is particularly well exposed in the vicinity of Batchtown, Calhoun County, Illinois, which is adjacent to St. Charles and Lincoln counties, Missouri. North of these localities the Kimmswick limestone is not known.

Broadly interpreted, it is seen that the Kimmswick occupies a narrow discontinuous belt along both sides of the Mississippi River from Ralls County, Missouri, and Calhoun County, Illinois, to Scott County, Missouri, and Alexander County, Illinois, a distance of about 180 miles, measured in a straight line. Beyond these limits the formation is covered by younger beds. On page 310 of his "Revision of the Paleozoic Systems," Ulrich states that the

[1] Aug. F. Foerste, "The Kimmswick and Plattin Limestones of Northeastern Missouri," *Jour. Sci. Laboratories, Denison University Bulletin*, Vol. XIX, 1920.

[2] *Ibid.*

Kimmswick appears at the surface again with characteristic fossils and lithology on the flanks of the Nashville dome near Aspen Hill, Kentucky. Over 40 feet of the upper part of the formation is here exposed. Likewise, outliers of the Kimmswick occur in south-central Tennessee and northern Arkansas. On page 369 of the "Revision," Ulrich states that the Kimmswick extends eastward around the southern side of the Nashville Island, into the Appalachian Valley, and westward around the southern border of Ozarkia to Colorado, where it is called the Fremont limestone.

THICKNESS OF THE KIMMSWICK LIMESTONE

No exact estimate of the total thickness can be obtained from field measurements of the strata, either in the type locality or in any other locality where the Kimmswick limestone is exposed, because the erosion which followed the deposition of this formation, wherever it is known in Missouri and Illinois, has removed the upper beds in varying degrees over the entire range of the formation. Consequently, where the top of the Kimmswick can be observed in the field, different horizons are seen to be overlaid by the Fernvale shale.

Concerning the occurrence of the Kimmswick in Missouri, Ulrich states that

> in the vicinity of Thebes, Illinois, and Cape Girardeau, Missouri, the Kimmswick includes at the top some 5 to 30 feet of crystalline limestone, containing *Echinosphaerites*, *Comarocystites*, and other peculiar fossils. This bed overlies another, easily recognized by the abundance of a large *Receptaculites* (*R. oweni*). Every outcrop in this area shows a different horizon at the top of the Kimmswick. That the Kimmswick at Thebes originally included even higher beds than are known there is indicated by later Trenton chert, found in broken down pre-Fernvale caverns.
>
> Going northward from the cape, the Kimmswick and Fernvale dip out of sight beneath younger formations. They come to the surface again between Establishment and Plattin creeks on the north limb of the syncline, but the outcrops in this area are not favorably situated for detailed study. . . . .
>
> At Rattlesnake Creek and Bushberg the top of the Kimmswick is formed by the *Receptaculites oweni* bed. One-fourth of a mile south, in the Glen Park quarry, the Fernvale rests on a lower bed. Then there is a long bluff to Grand Glaize Creek, showing how the contact descends still farther. Between Sulphur Springs and Kimmswick there is a minor syncline, in which the contact

rises a few feet. In the last exposure above the town of Kimmswick, the contact seems to have descended again. In 5 miles of almost continuous exposure the Fernvale cap maintains its thickness of a little more or less than 2 feet.[1]

The bed containing *Comarocystites* and *Echinosphaerites*, the youngest recognized fossil-bearing horizon in the Kimmswick, is best observed in southeastern Missouri at Cape Girardeau, where the thickness never exceeds 30 feet. *Comarocystites* has also been found in a quarry northwest of West Kimmswick (Imperial), Missouri, and south of Glen Park, both places being in the type area of Jefferson County. The occurrence of this form here is rare, and no distinct cystid horizon such as that at Cape Girardeau has been discovered.

Underlying the *Comarocystites-Echinosphaerites* zone, the *Receptaculites oweni* zone reaches a thickness of 68–80 feet in the vicinity of Thebes, on the Mississippi River in Alexander County, Illinois,[2] 6 or 7 miles southeast of Cape Girardeau. The fossil which gives the name to this zone is common throughout the entire thickness exposed here. Since this form is found at the bottom as well as at the top of the section, and since the younger cystid zone has been removed by erosion, it is likely that the thickness given does not represent the entire vertical extent of the *Receptaculites oweni* zone.

Underlying the *Receptaculites oweni* zone are the more highly fossiliferous lower beds, which, because they constitute the outcrops in the type locality, can be considered typical Kimmswick limestone. In the large quarry of the Glencoe Lime and Cement Company, just south of Glen Park station, 60 feet of this formation is exposed between the Plattin limestone below and the Fernvale above. Only the very highest bed here carries *Receptaculites oweni* in abundance.

In northeastern Missouri, the McCune limestone was assigned a thickness of 25–30 feet by Keyes in 1898,[3] and 50 feet in 1914.[4] The abundance of *Receptaculites oweni*, however, is the only basis for correlation of this formation with the Kimmswick of southeastern

[1] *Op. cit.*, pp. 309, 310.

[2] T. E. Savage, *Amer. Jour. Sci.*, Vol. XXV, p. 432.

[3] *Op. cit.*, p. 61.

[4] C. Keyes, *Scheme of the Stratigraphic Succession in Missouri.*

Missouri. Foerste[1] states that in Ralls County immediately north of the type locality for the McCune, the Kimmswick limestone (as broadly interpreted by Branson) reaches 100–125 feet thicknesses at several points. In Calhoun County, Illinois, the Kimmswick outcrops at the contact with the subjacent Plattin limestone, at Cave Spring on Madison Creek about 14 miles southwest of Batchtown. Above the contact, 53 feet of typical Kimmswick limestone occurs, with *Receptaculites oweni* present at the top.

It can be seen from the foregoing measurements that the maximum thickness of the formation is obscured by the lack of a complete section and by the erosion which preceded and followed the deposition of the Kimmswick. Synthesizing evidence from faunal zones, it seems likely that 160 feet is not too great a maximum thickness, that is, allowing 50 feet for the lower beds between the Plattin and the *Receptaculites oweni* zone, on the basis of exposures in Calhoun County, Illinois, and Jefferson County, Missouri; 80 feet for the thickness of the *Receptaculites oweni* zone, based on the maximum thickness at Thebes, Illinois, as measured by Savage; 30 feet for the upper cystid zone, the maximum figure given by Ulrich at Cape Girardeau. It has already been shown that the thickness allowed for the *Receptaculites* zone at Thebes does not represent the greatest thickness of that zone, so that it is not unlikely that the total thickness of the Kimmswick limestone approaches 200 feet.

LITHOLOGY

The Kimmswick limestone throughout its entire extent is easily recognized as gray to buff-colored, coarsely crystalline, heavily bedded limestone. The texture varies somewhat between widely separated outcrops, and in places chert nodules are sparingly present, but, on the whole, the formation is characterized by its extreme purity and uniformity of color and texture. In Cape Girardeau and Scott counties of southeastern Missouri, the Kimmswick has been metamorphosed into a pinkish to white-colored limestone which has the appearance of marble.

[1] *Op. cit.*, p. 177.

FAUNA OF THE KIMMSWICK LIMESTONE

Although the Kimmswick limestone has long been known as a highly fossiliferous formation, particularly in its lower beds, no thorough study of the fossils has ever been published. Early faunal lists published by Savage[1] are incomplete and not diagnostic. The most complete lists were published by Foerste[2] in 1920, of the fauna of the Kimmswick limestone, ¾ mile south of Thebes, Illinois, and in Ralls and northern Pike counties, Missouri. In the same paper on "The Kimmswick and Plattin Limestones of Northeastern Missouri," Foerste described some of the Kimmswick species, but did not add to our knowledge of the formation in its typical exposures in southeastern Missouri. In Bassler's *Bibliographic Index of American Ordovician and Silurian Fossils*, published in 1915, only four species are listed from the Kimmswick, none of which were from the type localities in Jefferson County.

For over a year the writer has been working on the description of the fauna of the Kimmswick limestone, particularly as it is exemplified in the typical localities near Kimmswick, Missouri. Much splendid material, collected by Dr. Stuart Weller from the vicinity of Glen Park, Missouri, as well as from Batchtown, Illinois, Ste. Genevieve County, and Cape Girardeau, Missouri, Independence County, Arkansas, was contributed to the task. This was supplemented by much additional material collected by the writer in the fall of 1923 near Kimmswick, Sulphur Springs, and Glen Park, Missouri, as well as from Calhoun County, Illinois. The entire collection is preserved in Walker Museum, University of Chicago.

On a basis of this study the following list has been drawn up, giving the faunal composition of the Kimmswick limestone as a unit. An asterisk precedes those species which do not occur in the collections studied by the writer, while those species in the Walker Museum collections which are not known to occur in the type localities in Jefferson County, near the village of Kimmswick, are italicized. Species restricted to the McCune zone are marked with two asterisks.

[1] T. E. Savage, *Amer. Jour. of Sci.*, Vol. XXV (1908), p. 432; *ibid.*, Vol. XXVIII (1909), p. 511.

[2] *Op. cit.*, pp. 186, 187.

Receptaculites oweni
Receptaculites cornutiformis sp. nov.
Ischadites iowensis
Streptelasma corniculum
?Dendrograptus sp.
Wellerocystis kimmswickensis
Comarocystites shumardi
Comarocystites obconicus
Comarocystites sp.
*Echinosphaerites aurantium
*Cyclocystoides cf. halli
?*Archeocrinus sp.*
Corynotrypa inflata
Prasopora grandis
Constellaria varia
Hallopora gigantea sp. nov.
Chasmatopora sublaxa
Chasmatopora reticulata
Escharopora patens sp. nov.
Escharopora confluens
Stictopora elegantula
Rhinidictya mutabilis
Eurydictya calhounensis
Pachydictya occidentalis
Lingula riciniformis galenensis
Orbiculoidea lamellosa
Crania trentonensis
Crania setigera
Platystrophia precedens
Platystrophia trentonensis
Platystrophia cumingsi
Platystrophia amoena
Platystrophia precursor angustata
*Platystrophia shepardi
Mcewanella raymondi
Dalmanella rogata
Dinorthis pectinella
Dinorthis meedsi
*Dinorthis meedsi germana
Plectambonites minnesotensis
Plectambonites gibbosus
*Plectorthis plicatella
Rafinesquina minnesotensis
Rafinesquina jeffersonensis sp. nov.
Rafinesquina deltoidea
Strophomena incurvata
Strophomena emaciata
Strophomena septata
**Strophomena trilobata
*Strophomena scofieldi
*Strophomena billingsi
Clitambonites diversus
Parastrophia hemiplicata
*Parastrophia hemiplicata var.
Anastrophia primigenia sp. nov.
Rhynchotrema kentuckiense varians
Rhynchotrema uniplicatum
*Rhynchotrema anticostiense
Zygospira recurvirostris
*Scenidium anthonense
*Schizambon sp.
*Triplecia sp.
Ctenodonta concinna sp. nov.
*Ctenodonta intermedia
Cyrtodonta billingsi
Cyrtodonta sulcata sp. nov.
Vanuxemia wortheni
Vanuxemia dixonensis
*Vanuxemia hayniana
Whitella scofieldi
**Fusispira nobilis
Ambonychia bellistriata
Ambonychia cf. affinis
Ambonychia sp.
*Ambonychia amygdalina
Byssonychia intermedia
Conocardium limatulum sp. nov.
?Modiolopsis sp.
Tryblidium rugosum sp. nov.
Cyrtolites retrorsum
Cyrtolites sp. ind.
Sinuites cancellatus
Bucania batchtownensis sp. nov.
Bucania punctifrons primaeva var. nov.
Phragmolites multinotatus sp. nov.
Lophospira bicincta

Lophospira lineata sp. nov.
**Hormotoma (?) major
Hormotoma trentonensis
Hormotoma gracilis var. angustata
Hormotoma gracilis var. sublaxa
**Maclurina manitobensis
**Maclurites sp.
*Platyceras cf. depressus
Liospira cf. progne
*Cyclospira bisulcata
Gyronema intermedium sp. nov.
*Cyclonema praecitum
*Trochomena umbilicatum
Holopea missouriensis sp. nov.
*Holopea pyrene
*Strophostylus tectilis
Hyolithes multicinctus sp. nov.
Pterotheca triangularis sp. nov.
Conularia trentonensis occidentalis var. nov.
**Actinoceras cf. distans
Cameroceras sp.
Endoceras proteiforme
**Spyroceras bilineatum
Orthoceras cf. amplicameratum
*Triptoceras cf. planoconvexum
Eoharpes welleri sp. nov.
Isotelus gigas
Homotelus laeviurus
Isoteloides kimmswickensis sp. nov.
*Remopleurides striatulus
Remopleurides missouriensis
*Remopleurides cf. canadensis
Illaenus depressicapitatus sp. nov.
Bumastus rowleyi
Bumastus billingsi
Thaleops ovata
Goldius slocomi sp. nov.
Proëtus canalis sp. nov.
Cyphaspis globosus sp. nov.
Haploconus tumidus sp. nov.
Acrolichas cucullus
Acrolichas aspratilis sp. nov.
Acrolichas subdisjunctus sp. nov.
Acrolichas antiquarius sp. nov.
Hemiarges tribulbus sp. nov.
Hemiarges leviculus sp. nov.
Encrinurus trentonensis
Ceraurus pleurexanthemus
Ceraurus globulobatus sp. nov.
Ceraurus sp. ind.
Ceraurinus platycanthus sp. nov.
Ceraurinus tenuisculptus sp. nov.
Pseudosphaerexochus subcircularis sp. nov.
Holia magnaspina sp. nov.
Heliomera raymondi sp. nov.
Sphaerocoryphe arachniformis sp. nov.
Dalmanites katharina sp. nov.
Pterygometopus callicephalus
Calymene senaria
Aparchites granilabiatus
Ceratopsis chambersi

In a few cases, new species listed in this paper were formerly included or compared with old species. When such cases were clearly apparent, the old species have not been put into this list. Where the case was not so clear, the old species was put into the list. Possible duplication from this cause, however, can affect but few of the species here recorded.

Of the 147 species listed, 116 are present in the collections studied by the writer. The 31 species marked with asterisks are not known in the collections of Kimmswick fossils in Walker Museum, and are taken from Foerste's lists mentioned above. Of the 116 species

studied in detail, 94 are known from the typical localities in Jefferson County, Missouri, while the remaining 22 occur in one or more localities for the formation, outside of the type area. Of the 116 species in the Walker Museum collection, 35 are new to science and to be described elsewhere by the writer, of which 32 are known to occur in the type localities. In addition, 1 new genus and 2 new varieties are described, of which but 1 of the varieties is unknown in the typical exposures.

CORRELATIONS WITHIN THE KIMMSWICK

It has been briefly shown how the post-Kimmswick erosion cut differentially into the formation so that different horizons are found subjacent to the Fernvale in different localities. As a consequence, such species as *Comarocystites* and *Receptaculites oweni* (when found in abundance), which are restricted to certain zones, are quite naturally not found in regions where erosion has removed the strata bearing them. The fact that neither *Comarocystites* nor *Echinosphaerites* are listed by Savage from the locality south of Thebes, Illinois, although both occur at Cape Girardeau, merely signifies, providing collections have been thoroughly and carefully made, that the cystid zone has been removed from the strata near Thebes. Correlations cannot be made nor can barriers be established on the presence or absence of but a few species from the strata of the localities under comparison. The Kimmswick limestone, broadly interpreted by Branson as a lithological unit, has a sufficient number of species common to all horizons to demonstrate that essential faunal homogeneity accompanies essential lithological homogeneity. That the Kimmswick limestone, broadly interpreted, is a faunal unit is shown by the following comparisons of species known from localities removed from the typical localities with those from the type area in Jefferson County.

THE TYPE LOCALITIES

At Glen Park, Missouri, about 4 miles south of Kimmswick on the Mississippi River, some 60 feet of Kimmswick limestone is exposed in the large quarry of the Glencoe Lime and Cement Company, which is located about $\frac{1}{8}$ mile south of the station of Glen

Park. Another smaller quarry in the bluffs on the river is adjacent to the station. Northward from Glen Park along the river to Sulphur Springs and nearly to Kimmswick, the Kimmswick limestone is exposed in almost continuous outcrop. An abandoned quarry $\frac{1}{8}$ mile north of Kimmswick, another at McLoon's, about 1 mile southwest of West Kimmswick, and a ledge on the wagon road $\frac{1}{4}$ mile northwest of Sulphur Springs have furnished many Kimmswick fossils. These fossil localities have been referred to above as the type localities for the formation, and strata from the basal 50 feet or less of the Kimmswick limestone are exposed in all. In comparison with other areas, the species from these type localities will be grouped and the various fossil localities near Kimmswick, Sulphur Springs, and Glen Park will be considered as one.

THEBES AND TYPE LOCALITIES COMPARED

The probability that the section at Thebes represents higher horizons in the formation is shown by the absence of the lower contact with the Plattin and the abundance of *Receptaculites oweni* at the base of the section. This species is an important horizon-marker in the Kimmswick, because although it is known throughout the formation, it is not abundantly found in the lower 50 feet, but is very common in the lower beds of the upper part of the formation. It is found practically throughout the section at Thebes, which Foerste states is nearly 70 feet in thickness, but is abundant only in the lower 30 feet. At Glen Park, the bottom of the *Receptaculite* zone is exposed at the very top of the section. While it is clear that the Thebes section represents later horizons than the strata exposed to the north in Jefferson County, the essential homogeneity of the fauna of the Kimmswick limestone is indicated by the similarity of fossil species in both localities. The following species occur in both areas:

Receptaculites oweni
Crania trentonensis
Crania setigera
Dalmanella rogata
Dinorthis pectinella
Parastrophia hemiplicata
Plectambonites minnesotensis
Rafinesquina jeffersonensis
Rhynchotrema kentuckiense varians
Strophomena emaciata
Strophomena septata
Clitambonites diversus
Zygospira recurvirostra
Cyrtolites retrorsum

Byssonychia intermedia
Illaenus depressicapitatus
Bumastus billingsi
Goldius slocomi
Thaleops ovata
Isotelus gigas
Acrolichas cucullus
Pseudosphaerexochus subcircularis
Ceraurus globulobatus

The following species listed by Foerste are not known in the collection from the type localities studied by the writer:

Parastrophia hemiplicata var.
Plectorthis plicatella
Scenidium anthonense
Schizambon sp.
Strophomena scofieldi
Triplecia sp.
Cyclomena praeciptum
Strophostylus textilis
Ambonychia amygdalina

The following species in Foerste's list probably occur at the type locality, but are included with the synonymy of other species:

Platystrophia shepardi
Rhynchotrema anticostiense
Holopea pyrene
Bumastus trentonensis
Ceraurinus cf. scofieldi
Remopleurides cf. canadensis
Acrolichas cf. robbinsi

It is seen, then, that of the 39 species listed above, 23 occur at both localities, and only 9 species listed from Thebes are clearly unknown in the type fauna. It is possible that these 9 species occur in the type fauna and have not yet been found, but whatever the cause of their absence in Jefferson County, the essential faunal similarity of the two localities is at once apparent.

BATCHTOWN, ILLINOIS, AND TYPE LOCALITIES COMPARED

Compared with the fauna of the extreme northern exposures of the Kimmswick limestone in Calhoun County, Illinois, the fauna of the type localities is even more strikingly similar, because essentially the same horizons are represented in both localities. Large collections were made in the vicinity of Batchtown, by Professor Weller and his students in 1906, and by the author in 1923. The best fossil localities are in Madison Hollow, $1\frac{1}{4}$ mile southwest of Batchtown, where the Kimmswick is 53 feet thick and in contact with the Plattin, and 1 mile north of Batchtown where fossil-bearing ledges outcrop near the main wagon road north from Batchtown. The texture, color, and fossils of the rock here are practically iden-

tical with those of the rock in the type localities, so that even with careful study the two cannot be distinguished.

The faunal similarity is not less striking than the lithological. Of the 94 species known from the type localities, 68 have been collected near Batchtown, 16 species known from Batchtown are not known from the type localities, whereas 26 species known from the type localities are not known at Batchtown. This discrepancy is not important because in each case where a species is known from one locality and not the other, the form is rare, and its discovery in one place and lack of discovery in the other must be considered fortuitous. The more common species are present at both localities, and essential faunal unity is clear.

FAUNA OF KIMMSWICK LIMESTONE IN RALLS AND NORTHERN PIKE COUNTIES COMPARED WITH TYPE FAUNA

Foerste[1] listed the species found by him at Sanders Branch and other localities in Ralls and northern Pike counties, Missouri. The fauna of the lower part of the Sanders Branch section is compared by Foerste with that of the Thebes locality. Nearby exposures show the Kimmswick in contact with the Plattin so that the exposures here represent the lowest and lower beds of the Kimmswick in this area. Considering these lower horizons as a unit for comparison, it is seen that of the 33 species listed, 26 are found in the typical localities in Jefferson County. Such forms as *Dalmanella rogata*, *Dinorthis meedsi*, *Plectambonites minnesotensis*, *Rhynchotrema kentuckiense varians*, *Strophomena incurvata*, *Endoceras proteiforme*, *Acrolichas cucullus*, *Pterygometopus callicephalus*, and *Remopleurides missouriensis* are common at both localities.

The upper part of the Sanders Branch section in Ralls County carries a fauna which is poorly preserved and little known. The same horizon outcrops at Sugar Creek and McCune station in northern Pike County. This horizon is the McCune limestone of Keyes, and is doubtfully considered as an upper zone of the Kimmswick by Foerste,[2] but is regarded as a younger formation by Ulrich.[3] The fauna is characterized by *Hormotoma* (?) *major*, *Maclurina*,

[1] *Op. cit.*, p. 187. [2] *Ibid.*, pp. 182, 183.

[3] *Bull. Geol. Soc. America*, Vol. XXII, No. 3, Pl. XXVII.

Maclurites, and *Fusispira nobilis* forms not known at any horizon in the typical Kimmswick of southeastern Missouri. The limestone of the McCune zone in Ralls County, at its base, is more coarsely granular and more crystalline than that in the underlying true Kimmswick, while at the top it is fine grained. Because of insufficient faunal and stratigraphic data, the McCune zone is only provisionally included in the Kimmswick.[1]

FAUNAL HOMOGENEITY OF KIMMSWICK

The foregoing comparisons clearly show the faunal unity of the Kimmswick limestone over its entire range of outcrop in Missouri and Illinois. While new faunal elements, which shall be emphasized later in correlating the Kimmswick with other Middle Ordovician formations, appeared from time to time during the progression of Kimmswick time, the aggregate of species living in the Kimmswick sea varied but little throughout. The uniformity of texture and color of the limestone supports the testimony of the fossils, that physical conditions varied almost none from beginning to end of Kimmswick time, throughout the area covered by the Kimmswick embayment.

CORRELATION OF KIMMSWICK LIMESTONE WITH STRATA ELSEWHERE

Field evidence as to the stratigraphic position of the Kimmswick limestone is at once meager and uncertain. It is known to rest upon the Plattin limestone, which is of Black River age, throughout its extent in Missouri and Illinois. Its upper limit is obscured by the prolonged erosion which followed Kimmswick time in Missouri and Illinois, after which subsequent submergence brought in a Fernvale fauna. Raymond expressed what was known concerning the age of the Kimmswick prior to 1916 in the following paragraph:

> According to Ulrich, the Kimmswick limestone at Thebes, Illinois, and Cape Girardeau, Missouri, has at the top a bed of crystalline limestone, from five to thirty feet in thickness, which contains *Echinosphaerites* and *Comarocystites*, among other fossils. The Kimmswick at this locality cannot be

[1] The reason for correlating the McCune with the Kimmswick by some of the Missouri geologists is the presence of *Receptaculites oweni* in both formations. This same fossil has led to the correlation of the Galena with the Kimmswick, the error of which will be shown later.

definitely placed in the section, except that it is post-Lowville. In the Nashville dome in Tennessee a formation correlated by Ulrich with the Kimmswick and containing *Echinosphaerites* has been found at Aspen Hill, where it is forty feet thick, and followed by the Hermitage, the Bigby, and the Catheys formations. The contact with the underlying formation is not shown but Ulrich states that there is no doubt that it rests upon the Carters, which is the equivalent of the Leray or Lowville of New York, so that it may be safely stated that here again the *Echinosphaerites* bed is post-Leray. At this locality we have the *Echinosphaerites* without *Christiania*, and the zone apparently corresponds to the lower zone at Chambersburg, Strasburg, and Bellefonte. In this case the formation containing *Echinosphaerites* is limited above by the Hermitage formation, a formation which cannot be correlated with any New York formation, but which corresponds to the Logana of Kentucky and is also found at Bellefonte above the zone of *Echinosphaerites*. The Hermitage is followed above by the Bigby limestone, which contains a fauna corresponding to that of the *Prasopora* zone, or Middle Trenton of New York and Ontario. The Kimmswick limestone, and the corresponding *Echinosphaerites* zone in Pennnsylvania and north central Virginia, may therefore be correlated with some confidence with the lower part of the Trenton of New York.[1]

The similarity of the Kimmswick fauna with that of the Prosser of southern Minnesota and northeastern Iowa was pointed out by Foerste[2] in 1920. Foerste also provisionally correlated the questionable McCune zone of northeastern Missouri, included by Branson in the Kimmswick, with the Prosser.

COMPARISON OF KIMMSWICK AND PROSSER FORMATIONS

The following species are common to the Kimmswick and Prosser formations:

Ambonychia affinis
Ambonychia amygdalina
Ambonychia bellistriata
Acrolichas cucullus
Acrolichas robbinsi
Byssonychia intermedia
Calymene senaria
Ceraurus pleurexanthemus
Chasmatopora reticulata
Clitambonites diversus
Crania trentonensis
Ctenodonta intermedia
Cyclospira bisulcata
Dalmanella rogata
Dinorthis meedsi
Endoceras proteiforme
Fusispira nobilis
Holopea pyrene
Hormotoma gracilis
Hormotoma (?) major
Hormotoma trentonensis
Ischadites iowensis

[1] P. E. Raymond, *Bull. Mus. Comp. Zoöl.*, Vol. LVI, No. 3, p. 240.

[2] *Op. cit.*, pp. 83, 84.

Isotelus gigas
Lingula riciniformis galenensis
Liospira progne
Parastrophia hemiplicata
Plectambonites gibbosus
Plectambonites minnesotensis
Plectorthis plicatella
Prasopora grandis
Pterygometopus callicephalus
Rafinesquina deltoidea
Receptaculites oweni
Rhinidictya mutabilis
Rhynchotrema increbescens
Sinuites cancellatus
Streptelasma corniculum
Strophomena billingsi
Strophomena emaciata
Strophomena scofieldi
Strophomena trilobata
Strophostylus textilis
Triptoceras planoconvexus
Zygospira recurvirostris

The genera *Aparchites*, *Bucania*, *Cameroceras*, *Cyrtodonta Eoharpes*, *Goldius*, *Gyronema*, *Hallopora*, *Halpoconus*, *Hemiarges*, *Illaenus*, *Modiolopsis*, *Orthoceras*, *Pachydictya*, *Phragmolites*, *Vanuxemia*, and *Whitella* are present in both formations, which although not specifically identical are in some cases very closely related.

Although 52 genera and 45 species are common to both formations, there is no basis for an exact correlation of horizons. Some of the species common to both are found in basal Trenton horizons in New York and elsewhere, and there is evidence which will be brought out later to show that these species may have reached the northern and southern Mississippi Valley by different routes and therefore probably at somewhat different times. The essential contemporaneity of the faunas as a whole, however, cannot be denied. This conclusion is based upon the striking similarity of many of the species and genera, the occurrence in both formations of such restricted forms as *Clitambonites diversus*, *Parastrophia hemiplicata*, and *Dinorthis meedsi germana*, and the close similarity of *Hemiarges tribulbus* and *Hemiarges wesenbergensis paulianus*, species representing a genus rare in America.

The zone of large gastropods, particularly *Fusispiras* and *Trochomenas*, *Cyclospira bisulcata*, *Strophomena trilobata*, and *Rafinesquina deltoidea* at the top of the Prosser may be equivalent of the McCune zone of the Kimmswick, but such an exact correlation cannot be made until the McCune fauna is better known. This gastropod zone is not known in the typical Kimmswick exposures in southeastern Missouri, and, as Foerste[1] indicated, is restricted to

[1] *Op. cit.*, p. 184.

areas north of the Cap au Gres fault. The fauna of the typical Kimmswick limestone is more similar to the fauna of the lower 9 feet of the Prosser at St. Paul, Minnesota, designated as the *Clitambonites* bed by Winchell and Ulrich,[1] than that of the overlying *Fusispira* bed. Many of the species common to both formations have no zonal significance, so that only a general correlation can be made. It seems likely, however, that with the exception of the McCune zone of northeastern Missouri, the Kimmswick limestone in its type exposures does not rise above the base of the *Fusispira* zone.

COMPARISONS OF KIMMSWICK AND GALENA FORMATIONS

Certain apparent faunal similarities between the Kimmswick limestone and the Galena dolomite of the upper Mississippi Valley have led to correlations of the two formations. Savage[2] in 1908 referred to the Kimmswick as the Galena-Trenton, and considered the second as the southern equivalent of the first. In 1909 he slightly altered his opinion as follows:

> Out of thirty-five species of fossils listed from the Mohawkian strata of Minnesota which are also found in the Kimmswick limestone of Illinois, nine appear below the Trenton, six of which persist into the lower Trenton beds; twenty occur in the lower division of the Trenton (Clitambonites bed), nine of which continue upward into the overlying division; twenty-four species occur in the middle division (Fusispira bed), while only a single one of these is found in the upper division (Maclurea bed). From these facts the Kimmswick limestone is thought to correspond in time, with some part of the middle division of the Trenton (Fusispira bed) of the upper Mississippi valley.[3]

Ulrich believes that the Kimmswick should not be placed so high in the section. Referring to the correlation of the Galena and Kimmswick, he says:

> By discovery of lower to middle Galena, typical in fauna and rock, resting on upper Kimmswick limestone in Pike and Lincoln counties, Missouri, the error of this supposition is now established. We know further that the lower Galena (Prosser limestone) fauna underlies the base of the typical Trenton section in New York, and that it precedes the corresponding boundary also in Kentucky. Moreover, a slight unconformity at the top of the bed containing

[1] *Geol. and Nat. Hist. Surv. Minnesota*, Vol. III, Part 2, pp. xcviii and xcix.

[2] T. E. Savage, *Amer. Jour. Sci.*, Vol. XXV, p. 432.

[3] *Ibid.*, Vol. XXVIII, pp. 511, 512.

the Prosser limestone fauna in New York and Kentucky suggests a hiatus that probably represents the middle and possibly also the upper Galena. At least two-thirds of the Galena, plus the Kimmswick, therefore, belong between the base of the *Prasopora simulatrix* bed, which is usually counted the basal member of the typical Trenton, and the top of the Black River group in Oneida County, New York.[1]

The presence of typical "lower to middle Galena" resting upon the Kimmswick in Pike and Lincoln counties, Missouri, has not been detected by other geologists who have worked in that region. Ulrich does not state that the lower Galena in this area represents the "lowest" or basal beds of the formation farther north, that is, those horizons which can be correlated with the Prosser. From the striking faunal similarity between the Kimmswick and Prosser, the logical conclusion is that the Kimmswick rises at least as high in the section as the Prosser, so that one would not expect to find basal Galena overlying the Kimmswick. In regard to Ulrich's correlation of the Kimmswick and Galena with strata in the typical Trenton section of New York, more will be said later, but it should be mentioned here that in this paper the *Prasopora simulatrix* bed in New York is considered middle rather than basal Trenton because of its occurrence in the middle of the section at Trenton Falls. On this basis the Prosser is correlated with basal Trenton. Following Raymond and others, the Leray fauna is considered the top of the typical Black River.

As in other Trenton formations, a large element in the Kimmswick fauna represents species that survived Black River time. In the upper Mississippi Valley, the Decorah and Platteville formations represent early Mohawkian time, while in the lower Mississippi Valley, this epoch is represented by the Plattin (including the Auburn chert) formation.

The following species are common to the Kimmswick and top of the Plattin formation of eastern Missouri:

Strophomena incurvata	Lophospira bicincta
Cyrtodonta billingsi	Spyroceras bilineatum
Cyrtolites retrorsum	Isotelus gigas
Hormotoma gracilis angustata	Triptoceras planoconvexum

[1] "Revision of the Paleozoic Systems," *Bull. Geol. Soc. Amer.*, Vol. XXII, No. 3, pp. 524, 525.

The following are common to the Kimmswick limestone and the Auburn chert of Lincoln County, Missouri:

Streptelasma corniculum
Rafinesquina minnesotensis
Strophomena incurvata
Zygospira recurvirostris
Cyrtodonta billingsi
Cyrtolites retrorsum
Hormotoma gracilis sublaxa
Liospira progne
Strophostylus textilis
Spyroceras bilineatum
Triptoceras planoconvexum
Ceraurus pleurexanthemus
Isotelus gigas

The following species are found in the Kimmswick limestone and the Decorah shale of northeastern Iowa and Minnesota:

Ceratopsis chambersi
Ceraurus pleurexanthemus
Chasmatopora reticulata
Corynotrypa inflata
Cyrtodonta billingsi
Dalmanella rogata
Dinorthis pectinella
Endoceras proteiforme
Escharopora confluens
Lophospira bicincta
Pachydictya occidentalis
Prasopora grandis
Pterygometopus callicephalus
Rhinidictya mutabilis
Scenidium anthonense
Sinuites cancellatus
Strophomena incurvata
Strophomena septata
Strophostylus textilis
Whitella scofieldi
Zygospira recurvirostris

The following species are found in the Kimmswick and the Platteville limestone of eastern Iowa and Minnesota, and western Wisconsin and Illinois:

Orthoceras amplicameratum
Endoceras proteiforme
Ceraurus pleurexanthemus
Pterygometopus callicephalus
Chasmatopora sublaxa
Cyrtodonta billingsi
Hormotoma gracilis angustata
Lophospira bicincta
Rafinesquina minnesotensis
Scenidium anthonense
Sinuites cancellatus
Strophomena incurvata
Thaleops ovata
Vanuxemia dixonensis
Zygospira recurvirostris

Of the foregoing 29 species common to the Kimmswick and formations of Black River age in the Mississippi Valley, 14 are known to have persisted into Trenton times in the upper Mississippi Valley, and are present in the Prosser. All of the remainder are known in Trenton formations farther east, with the exception of the follow-

ing, which have not previously been found in strata younger than Black River: *Chasmatopora sublaxa*, *Escharopora confluens*, *Pachydictya occidentalis*, *Scenidium anthonense*, *Vanuxemia dixonensis*, *Strophomena septata*, and *Whitella scofieldi*. All of these are local Mississippi Valley species of genera common to the entire Mohawkian series. There is no good reason why they should not have persisted into Trenton times, and their absence in the Prosser is more difficult to explain than their presence in the Kimmswick.

KIMMSWICK COMPARED WITH THE TYPICAL TRENTON OF NEW YORK AND ONTARIO

The type locality for the Trenton is at Trenton Falls, New York. Since the formation subjacent to the Trenton is not exposed in the type locality, a section at Rathbone Brook, a few miles east of Trenton Falls, is used to supplement the one at Trenton Falls. The sequence of strata in this composite section, with the Utica shale above and the Leray-Black River below, is summarized by Raymond[1] as follows:

	Feet
7. Light-gray, coarse-grained lithified coquina in thick beds, *Rafinesquina, deltoidea*, *Hormotoma trentonensis*, and other fossils	26
6. Thin-bedded blue limestone with shaly partings. *Rafinesquina deltoidea* the common characteristic fossil	92
5. Thin-bedded blue limestone with thick shaly partings. *Prasopora simulatrix* and other common Trenton fossils abundant	100
4. Thin- and thick-bedded limestone, dark in color and fine grained. *Diplograptus amplexicaulis* a common fossil	35
3. Thin-bedded dark limestone with *Triplecia extans* and other fossils	20
2. Thin-bedded dark limestone with some interbedded coarse-grained layers. *Cryptolithus tesselatus* the characteristic fossil. *Trematis terminalis*, *Platystrophia trentonensis*, *Calymene senaria*, and many other fossils present	41
1. Thin-bedded gray limestone with an abundance of *Dalmanella rogata* and some other fossils	32

The section across the International Boundary in Ontario, according to Raymond, is essentially the same except for local developments. The Lower Trenton beds contain a large number of

[1] P. E. Raymond, *Bull. Mus. Comp. Zoöl.*, Vol. LVI, No. 3, p. 253.

recurrent Black River species, as high as 100 feet above the base of the formation, indicating continuous sedimentation after the Leray, with the Trenton fauna gradually replacing that of the Leray.

The great difficulty of any exact correlation between the Kimmswick and the New York Trenton east of Trenton Falls is that the greater part of the Trenton fauna is composed of wide ranging, cosmopolitan species with little value in correlation. Furthermore, many of the most characteristic Kimmswick species were never represented in northern New York. Referring to the difference between the Black River and Trenton in the type area, Raymond[1] states his belief that all beds above the Leray-Watertown horizons belong to the Trenton, and that *Calymene*, *Platystrophia*, and *Parastrophia* are common fossils not found in the Black River of that region, while *Gonioceras anceps*, *Hormoceras tenuifilum*, and *Dalmanella gibbosa* are fairly common species of the Black River which do not persist into the Trenton. He states further that *Columnaria halli* is a safe indication of the Black River.

As in the comparison of the Kimmswick with the Prosser of Minnesota, many species could be listed common to the Kimmswick and both the typical Trenton and the typical Black River. Nevertheless, not one of those species listed by Raymond as typical of the Black River and limited to that series in New York and Ontario is known from the Kimmswick. In addition to this, the presence in the Kimmswick of five species of *Platystrophia*, *Calymene senaria*, and *Parastrophia hemiplicata*, is strong evidence that the Kimmswick limestone is at least as young as the Lower Trenton of the type section.

The upper limit of the Kimmswick cannot be inferred from a comparison with the New York section because of the total absence of such species as *Prasopora simulatrix*, *Cryptolithus tesselatus*, and *Triarthrus becki*, which mark different horizons in the typical Trenton section.

Comparison of the Kimmswick fauna with Trenton faunas in other localities leads to the same result. In Bassler's list of species from the Trenton at various localities in Canada, New York, and

[1] *Summary Report, Geol. Surv. Dept. of Mines, Ottawa* (1914), p. 350.

the Ohio Valley, 28 are known in the Kimmswick. Of these the following species are not known in strata older than Trenton:

Ambonychia amygdalina
Ambonychia bellistriata
Bucania punctifrons
Bumastus billingsi
Conularia trentonensis
Lingula riciniformis
Parastrophia hemiplicata
Rafinesquina deltoidea
Remopleurides striatulus
Rhynchotrema increbescens
Stictopora elegantula
Streptelasma corniculum
Strophomena trilobata
Vanuxemia wortheni

Of the foregoing species, none are known to be restricted to any well-marked zone in the Trenton with the exception of *Rafinesquina deltoidea*, which together with *Hormotoma trentonensis* characterizes the top of the section at Trenton Falls. Both of these forms are present in the Kimmswick, the former in some abundance, but an exact correlation cannot be made on this basis alone, because there is no good evidence that these species do not occur at Lower Trenton horizons outside of the type area.

Since the most characteristic elements of the Kimmswick fauna are not found in any other formations of interior North America, contemporary horizons must be looked for along the route followed by certain peculiar trilobites and cystids in migrating into the lower Mississippi Valley. That this route lay through the Appalachian Valley will be demonstrated in the following discussion.

CORRELATION OF THE KIMMSWICK WITH STRATA IN PENNSYLVANIA AND VIRGINIA

Correlation of Mohawkian horizons in the Appalachian Valley has been made in many cases on the position of the *Echinosphaerites* beds. Ulrich states that this cystid is present in three horizons, one below and two above the Lowville. The evidence for the upper two occurrences is given in the *Mercersburg-Chambersburg Folio* by Stone. These horizons are both to be found in the limestones grouped together as the Chambersburg limestone, which is underlaid by strata correlated with the Stones River and overlaid by the Martinsburg shale, which in its lower part carries *Triarthrus becki*, *Cryptolithus tesselatus*, and other Trenton species. The following

is the type section of the Chambersburg limestone as given by Stone and subsequently rearranged by Raymond:[1]

	Feet
Calcareous shale and shaly limestone, with *Christiania trentonensis*, *Plectambonites asper*, *P. perium*, *Oxoplecia*, *Parastrophia hemiplicata*, etc. *Echinosphaerites* in the upper 10 feet	150±
Dark-gray, largely thin-bedded limestone with *Nidulites favus*, *Ampyx*, *Plectambonites asper*, etc	237±
Dark-gray limestone in which *Echinosphaerites* is very common, *Ampyx*, *Receptaculites*, *Oxoplecia*, and brachiopods also common	60±
Grayish, dense, thin-bedded limestone with *Tetradium cellulosum*, *Zygospira recurvirostris*, etc	150±

At Strasburg, Virginia, these two *Echinosphaerites* horizons occur in essentially the same manner, which, according to Raymond, is in striking accord with their occurrence in Norway, where the lower *Echinosphaerites* bed occurs first without *Christiania* and then at a higher horizon with that species. Raymond's conclusion regarding the age of these beds in America is summarized in the following paragraph:

> At Bellefonte, Pennsylvania, according to observations made by Mr. R. M. Field and the writer, a zone of dark limestone, containing such typical Leray (Black River) species as *Columnaria halli* and *Maclurites logani*, is followed by more argillaceous limestone containing *Echinosphaerites* and a large number of other fossils. Christiania has not yet been found in the Bellefonte section, but this section does not definitely show that the *Echinosphaerites* zone is there younger than the Leray–Black River of New York. As shown by Mr. Field, there is essential agreement between the section at Bellefonte and that at Chambersburg and Strasburg, so that all three of these occurrences of *Echinosphaerites* may be dated definitely as post-Leray.

The third and oldest horizon of *Echinosphaerites* in America is in the Ottosee formation of eastern Tennessee and southwestern Virginia, which Ulrich considers older than the Lowville. There is some evidence that this zone of *Echinosphaerites* is as young as Black River, but associated fauna precludes any correlation with the Kimmswick.

The evidence from the cystid content of the Kimmswick limestone at Cape Girardeau, Missouri, where *Echinosphaerites* occurs without *Christiania* as has been shown previously, is strongly in

[1] *Op. cit.*, p. 238.

support of a correlation of the Kimmswick with the corresponding *Echinosphaerites* zone (Middle) in Pennsylvania and Virginia, which in turn may be correlated with the Lower Trenton of New York. It is seen that although entirely different evidence is used in working out the relationship of the Kimmswick with strata in the Appalachian region from that used in comparison with formations of the interior, the same general conclusion is reached, that the Kimmswick is of early Trenton rather than late Black River age.

ORIGIN OF THE FAUNA OF THE KIMMSWICK LIMESTONE

It has been previously shown that many of the most common species in the Kimmswick fauna are wide ranging, perhaps cosmopolitan forms, common to strata of various ages in Black River and Trenton formations. These species are present in the Kimmswick, Prosser, Chambersburg, and Lower Trenton of New York and Ontario, but they give no clue as to the place of their origin, other than that many are autochthonous North American types.

We have seen that 52 genera and 45 species are common to the Kimmswick of the southern and the Prosser of the northern Mississippi Valley, and from certain of these forms have inferred essential contemporaneity for the two formations. Many of these species are found in Mohawkian strata elsewhere, and may have reached the Prosser by a different route than that followed in migrating to the more southern region. That the basins in which the Prosser and Kimmswick were deposited were actually disconnected is rather strikingly shown by a study of the trilobite fauna of the latter formation.

ORIGIN OF THE KIMMSWICK TRILOBITES

The trilobites are undoubtedly the most interesting and characteristic element in the Kimmswick fauna. Twenty-four genera and 34 species are known, of which number, 1 genus and 20 species are new to science. Ten of these genera, *Acrolichas*, *Eoharpes*, *Calymene*, *Ceraurus*, *Goldius*, *Isotelus*, *Haploconus*, *Hemiarges*, *Illaenus*, and *Pterygometopus* are present in the Prosser, while 14 are unknown in that formation. Only *Ceraurinus*, *Ceraurus*, *Eoharpes*, *Pterygometopus*, *Thaleops*, *Illaenus*, *Isoteloides*, *Isotelus*, and *Encrinurus* are known in the typical Black River Decorah, Platteville, Plattin, and Leray faunas of interior North America. It is apparent that

the greater number of trilobite genera in the Kimmswick cannot be explained as survivors of earlier times in the same region, and equally clear that they could not have been derived from the contemporaneous Prosser fauna to the north. On the other hand, the absence of the characteristic Kimmswick trilobite fauna in the Prosser argues strongly against free intermingling of early Trenton faunas after their arrival in the northern and southern basins of the Mississippi Valley.

The route followed by such invading Russian genera as *Remopleurides*, *Pseudosphaerexochus*, and *Sphaerocoryphe* is known to have been rather definitely restricted from Chazy to Upper Trenton times. These genera are known from a belt along the eastern Appalachians from Gaspé to Alabama in western Tennessee, and in the Kimmswick of Missouri and Illinois, while they are only rarely found in Mohawkian strata of the interior. With these invading trilobites is associated the Russian cystid, *Echinosphaerites*, similarly restricted in range, and together they form a conspicuous element of the Kimmswick fauna. These invading types made their first appearance in the Walchow, Kunda, and Dubowiki formations of Russia, the first two being equivalent to the American Beekmantown, and the third of Stones River age.[1] Arriving in Northeastern North America they followed the belt along the eastern Appalachians, being present at various horizons of Chazy and Mohawkian strata, but leaving no record of their arrival in the lower Mississippi Valley until that found in the Kimmswick. Of this fauna *Remopleurides* and *Sphaerocoryphe* are common at all horizons in the Kimmswick. That both are absent from the Prosser argues against free intermingling of the early Trenton faunas after their arrival in the northern and southern parts of the Mississippi Valley. How many native American types came into the Kimmswick Basin with the invaders by what may be called the Appalachian Valley route cannot be estimated, although it is safe to assume that some did. On the other hand, there is evidence that other routes were followed by many species during the great Mohawkian submergence. Such invading Russian genera as *Eoharpes*, *Ceraurus*, *Pterygometopus*, and the brachiopod *Clitambonites*, as well as native

[1] P. E. Raymond, "Correlation of the Ordovician Strata of the Baltic Basin with Those of Eastern North America," *Bull. Mus. Comp. Zoöl.*, Vol. LVI, No. 3, Pl. VIII.

American forms such as *Isotelus*, *Isoteloides*, and *Thaleops*, are found at various localities in the great interior basin. Of the 14 genera of trilobites found in the Kimmswick and not known in the Prosser, only the three discussed above give clear evidence of their westward migration through the circuitous Appalachian Valley route. The other 11, while not giving definite clue as to their migration route into the Kimmswick Basin, strongly suggest a barrier in early Trenton times between the northern and southern divisions of the Mississippi Valley.

INDICATIONS OF A PACIFIC FAUNULE IN THE KIMMSWICK OF ARKANSAS

Previously undifferentiated from the lower part of the Polk Bayou limestone, the Kimmswick limestone is present in Independence County, Arkansas, with characteristic lithology and carrying such typical species as *Illaenus depressicapitatus*, *Goldius slocomi*, and *Mcewanella raymondi*. Other species fill in to make a characteristic Kimmswick assemblage. A species of *Anastrophia* is found associated with these Kimmswick fossils (*A. primigenia*), which could not be derived from any known Ordovician species in Eastern North America. *Anastrophia primigenia* is exceedingly common in the Kimmswick at the O'Flynn mine, Independence County, Arkansas, and is present also in smaller numbers in the Kimmswick at Cape Girardeau, Missouri. North and east of Cape Girardeau, it is unknown. The range of the peculiar Kimmswick brachiopod, *Mcewanella raymondi*, is similar, being rather common in the Kimmswick of Independence County, Arkansas, and becoming less common in the formation to the north and east. It is known from the Kimmswick limestone in Cape Girardeau, Ste. Genevieve, and St. Louis counties, Missouri, as far north as Minke, Missouri. These two species, known only in the Kimmswick, point to the possible origin of part of the Kimmswick fauna in Western North America, or to have been carried into the interior by a Pacific invasion. Earlier strata to the east, south, and north have no record of either *Mcewanella* or *Anastrophia*, and it is clear from the occurrence of these brachiopods in the Kimmswick that they become less plentiful to the east and north. The full importance of this faunule cannot be known until careful faunal and stratigraphic studies are made of the Kimmswick in Arkansas and Colorado.

THE ORIGIN OF SWIMMING WOMAN CANYON, BIG SNOWY MOUNTAINS, MONTANA, AN EXAMPLE OF A PSEUDO-CIRQUE FORMED BY LANDSLIDE SAPPING

O. W. FREEMAN
Northwestern University, Evanston, Illinois

ABSTRACT

The Big Snowy Mountains, Montana, contain canyons which are cirque-like but not of glacial origin. These "pseudo-cirques" are believed to result from landslide sapping that follows erosion of shale overlain by thick limestone. These canyons develop in flat-topped anticlines with steeply dipping limbs.

The Big Snowy Mountains are in central Montana east of the Little Belt Mountains. They result from a canoe-shaped uplift that had nearly flat summit, and are 20 miles long by half as broad. Pennsylvania and all younger rocks have been eroded from the mountain mass. The formations exposed in the mountains are as follows:

Age	Formation	Approximate Thickness in Feet
Mississippian	Madison limestone	1,700
Devonian (?)	Jefferson limestone	300
	Unconformity (?)	
	Meagher limestone conglomerate	300
Cambrian	Wolsey shale with few limy and sandy beds	700
	Flathead quartzite conglomerate	80–100
	Angular Unconformity	
Algonkian	Belt Series, fissile shale	200

The Madison limestone forms the greatest part of the mountains. The Cambrian is exposed only in the deeper canyons, and the Belt is exposed only in the bottom of Swimming Woman Canyon. The canyons radiate outward from the axis of the canoe-shaped uplift. The original summit of the Big Snowies was where Half Moon Pass is now. The present summits of the Snowies are on either side of this pass, and attain an altitude of 8,700 feet, or about 2,500 feet above the canyon floor of Swimming Woman Creek, which

heads in Half Moon Pass. The strata dip gently away from the mountain axis for 1 or 2 miles on either side, then steepen to 10–15° on the north and 30–45° on the south at the mountain edge. The north slopes of this mountain group are, therefore, over twice as long as the south slopes.

Upon examining the Big Snowy topographic map, one is struck by the cirque-like character of some of the canyons, especially of

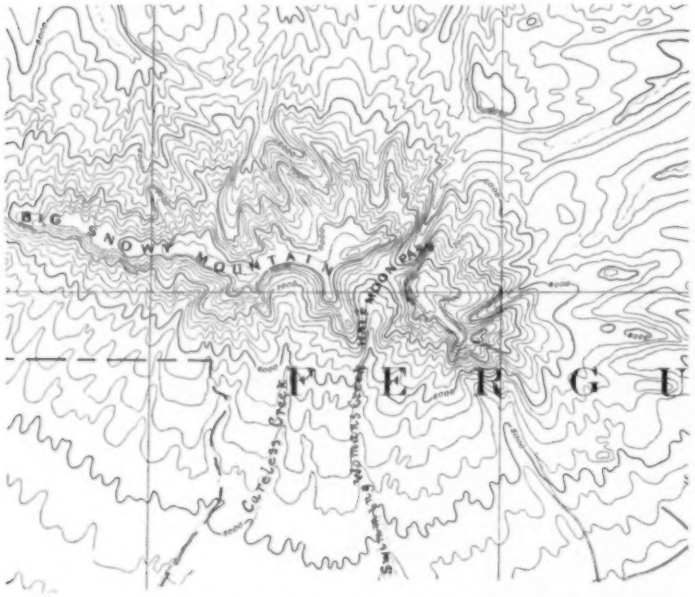

FIG. 1.—Section of topographic map from the U.S. Geological Survey Big Snowy Mountain Sheet, Montana, Reconnaissance Map, showing cirque-like character of some of the canyons, especially of Swimming Woman and Careless creeks.

Swimming Woman and Careless creeks (Fig. 1). The entrances to the canyons are very narrow, while toward their heads the canyons broaden out into steep-walled amphitheaters, some of which are separated from each other by walls only a few yards wide, resembling the Garden Wall Glacier Park. The canyons of the Big Snowy Mountains that resemble glacier cirques cannot be of glacial origin for the following reasons: (1) A careful search has revealed no

trace of moraines, either within the canyons or outside them near the mountains. (2) Soft, weathered rock occurs on the surface of bed rock in the canyons from which glaciers would certainly have removed it. (3) Many large pinnacles, arches, and loose detritus of weathering are found along the cliffs especially at the entrances to the canyons. (4) No rock-basin lakes, truncated ridges, glacial striae, beveled rocks, glacial polish, or other evidences of glaciers were seen.

The canyon of Swimming Woman Creek is the best "pseudo-cirque." The first half-mile of the canyon is so narrow that there is little room for more than the creek and a road. Its walls are of limestone that dips south, downstream, at an angle of 40°. Above this the canyon begins to widen out rapidly and the stream meanders over a relatively flat floor for nearly a mile. This corresponds to the outcrop of the soft Wolsey shale, while the narrow part of the canyon is eroded from the Madison, Jefferson, and Meagher limestones. It is these limestones that determine the local base level of the creek. Above the flat, the creek and its tributaries have incised themselves in narrow valleys a few hundred feet deep. These little valleys are separated by flat-topped rock terraces of Flathead quartzite, below which is the shale of the Belt Series in which the streams are rapidly deepening their valleys. Beyond this zone of rock terraces is a zone of landslides that extend around the "pseudo-cirque" between the cliffs and the rock terraces and valley flat. The landslide zone is more than half a mile across at the head of the valley, and is determined by the outcrop of the soft Wolsey shale, the rapid weathering, slumping, and removal of which permits the overlying limestone beds to slip down in great blocks. One of these landslide blocks is over a quarter of a mile long. So complete is the chaos wrought by the landslides that few exposures of Wolsey shale in place can be found. Above the landslide zone are nearly vertical cliffs, only partly masked at their base by talus that grades downward into the landslides. The cliffs circle nearly around the "pseudo-cirque" and form the narrow entrance walls to the canyon. At the head of the canyon, they have been removed almost to the base of the limestone to form Half Moon Pass, which is a mile broad. Swimming Woman Creek has numerous tributaries. They start in springs determined by the outcrop of Wolsey

shale in the landslide zone and several of them meander across the valley flat to join the main stream. Swimming Woman Canyon is thus divided into five parts: (1) narrow entrance, (2) valley flat, (3) rock terraces, (4) landslide zone, (5) cliffs (Fig. 2).

The origin of the "pseudo-cirques" in the Big Snowy Mountains is believed to be chiefly the result of sapping by landslides headward and sideward from original narrow river valleys, that would radiate outward from the anticlinal axis. A narrow canyon would first be eroded in the 2,300 feet of Paleozoic limestone, and no landslides could occur until the soft Cambrian shales had been reached. Then

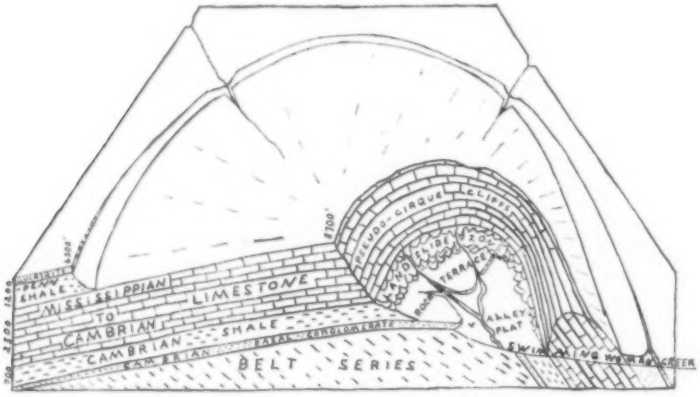

FIG. 2.—Idealized block diagram of Swimming Woman Canyon

the process would begin, and the limestone walls would be undermined and fall with the removal of the shale. Since only resistant limestone is exposed at the canyon mouth, landslide sapping could not operate there, and the valley entrance would remain narrow, thus simulating a glacial valley. The length of the narrow entrance gorge would depend on the thickness of the hard limestone and its dip. Erosion would proceed very slowly here compared to the rate possible in the shale. Therefore the stream and its tributaries would soon cut through the shale to this local base level and begin to meander. This meandering would cause the canyon to broaden and lengthen, mostly from the bottom up, by undermining and causing landslides, which process may be called "landslide sapping."

The width of the valley would increase with the greater thickness of the shale exposures farther upstream without any meandering of the stream, but such meandering hastens the process. Some of the shale might be partly squeezed out by the pressure of the limestone beds above.

The resulting débris would be removed by the meandering streams down to a level determined by the local base level of the hard limestone at the canyon mouth. As time goes on, the canyon walls recede far enough from the stream to permit a nearly level valley flat to begin to develop at the middle of the valley just above the limestone "gates" of the canyon. The landslide zone, with the precipitous cliffs above, that result from the process of "landslide sapping," would recede in three directions from the valley flat and the canyon would assume a cirque-like form. Since the hard limestone beds are about 2,300 feet thick in the Big Snowies, a "pseudo-cirque" wall approaching that height would result.

If a hard layer of rock underlies the shale and is, in its turn, underlain by another series of shale beds, one would expect that another "pseudo-cirque" could develop inside the first. In Swimming Woman Canyon the Cambrian basal conglomerate is underlain by Belt shale without a "pseudo-cirque" being formed, probably because the rock terrace resulting from the hard basal quartzite conglomerate has been so recently incised by the streams that they are not yet at base level and so are not meandering. Also this hard layer is less than 100 feet thick, and the "pseudo-cirque" walls could not be much higher than this, so they would never be strongly developed.

The conditions favorable for the development of "pseudo-cirques" by landslide sapping are believed to be as follows: (1) An anticline must have nearly flat strata on top if a dome, or along the axis if canoe-shaped, and dip quite steeply on the limbs. (2) The flat-lying strata on the crest of the anticline must provide sufficient area to permit a "pseudo-cirque" to develop. (3) Resistant beds, like limestone, must be underlain by easily eroded beds like shale. (4) The hard layers should be relatively thick, as the height of the "pseudo-cirque" walls depends directly on this thickness. In the Big Snowy Mountains the hard limestone layers are three times as thick as the shale.

ON THE FORCE OF CRYSTALLIZATION OF CALCITE[1]

E. P. ROTHROCK
University of South Dakota

ABSTRACT

The geologic evidence indicates that the calcite in the Nussbaum formation of Cimarron County, Oklahoma, exerted great force in crystallizing. This force was sufficient to move considerable masses of rock material and to split grains of quartz sand.

It has long been a question whether growing crystals could exert a force sufficient to move anything in the line of their growth. Experimental evidence on both sides of the question has been offered but there is still a diversity of opinion. On one side are those who contend that tremendous forces are exerted as indicated by the salt domes of the Gulf Coast and the characteristics of certain veins. On the other side are those who hold that though such forces may exist there is no reason to believe that they are of any geological consequence. It is proposed to set forth in this statement some evidence which seems to confirm the former belief.

That growing crystals do exert force has been demonstrated by Becker and Day[2] and also by Taber.[3] The first two experimenters succeeded in raising a kilogram-weight by causing a crystal of alum to grow under it. Taber also caused cracks to form in a porous battery jar by the crystallization of copper sulphate, and a glass container was broken in the same way.

Some geological evidence of the potency of this force was found by the writer during a study of the Nussbaum formation in Cimarron County, Oklahoma. This formation is largely a fine brown sand which has been cemented near the surface by calcite. The field

[1] Published by permission of former director of the Oklahoma Geological Survey, Mr. C. W. Shannon.

[2] G. F. Becker and A. L. Day, "The Linear Force of Growing Crystals," *Proc. Wash. Acad. Sci.*, Vol. VII (1905), pp. 283–88.

[3] S. Taber, "The Growth of Crystals under External Pressure," *Amer. Jour. Sci.*, Vol. XLI (4th ser., 1915), pp. 532–56.

evidence shows that this cement is a caliche, the calcite which was originally disseminated through the formation having been concentrated at the surface by the evaporation of ground water. Thicknesses of 20–40 feet of this caliche are exposed along the bluffs of the Cimarron and Beaver rivers, and in all sections exposed there is a marked decrease in the percentage of sand and a corresponding increase in the percentage of calcite toward the surface. Loose sand with only enough calcite to make a lively effervescence occurs at the bottom of the sections, while the tops are composed of very solid rock, about 10 per cent of which is sand and 90 per cent calcite. Between these two extremes there is a complete gradation in all sections, irrespective of their positions in the formation. Such a diminution in the amount of sand in this sort of rock could only come about by the pushing aside of the sand grains to make room for the newly crystallizing calcite. As more calcite was added the grains were pushed farther apart. Since the most rapid evaporation takes place at the surface, the most calcite was deposited there and the sand grains pushed farthest apart. With increasing depth, evaporation and precipitation became less and less, and this caused the gradation mentioned above.

Further evidence of the force exerted by growing calcite was found in certain quartz grains which had been split by the crystallizing calcite. These split grains were discovered during the microscopic study of a slide made from a dense, porcelain-like specimen from the top of the Nussbaum caliche. Almost every grain in the slide showed cracks filled with calcite, and in some the parts of the grain had been moved slightly, as shown in the camera lucida drawing (Fig. 1*C*). In several cases, however, the grains were cut in two by very pronounced veins, the opposite parts having been shoved aside to the full width of the vein. Two such veins are shown in the camera lucida drawings (Fig. 1*A* and *B*). The widest of these veins (Fig. 1*A*) measured 0.225 mm.

Several facts observed indicate that the grains were split by calcite crystals. The most obvious is the perfection with which the edges on opposite sides of the vein match. If the calcite were removed from any of the three grains shown in the drawings, the pieces could be put back together so that the edges would almost

fit and the original shape of the grain would be restored. This shows that in each case we are dealing with a single grain, the parts of which have been moved away from each other without changing their relative positions and without notable rotation of the parts after separation.

In several instances incipient cracks were seen, like the one marked *X* in Figure 1*A*, in which the calcite had filled the crack at the open end and sprung the chip, but had not yet split it off from the grain. Such cracks are apparently the beginning of the process which leads to the veins shown in *A* and *B* of Figure 1.

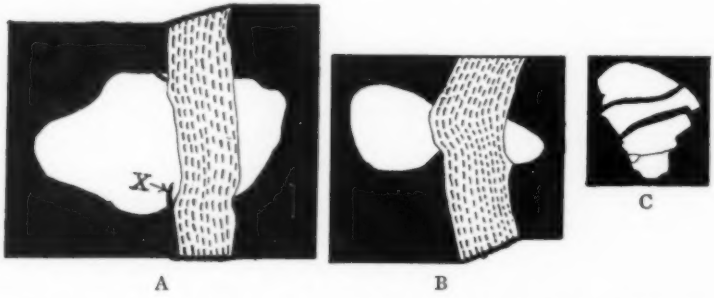

FIG. 1.—Camera lucida drawings showing quartz sand grains split by crystallizing calcite. Quartz grains shown in white, calcite matrix in black, calcite veins as dashed areas.

It could hardly be argued that the veins had been split by other means, the calcite veins simply filling cracks already made. The exactness with which the opposite sides of the split grains fit has been mentioned. The sands of the Nussbaum formation are alluvial deposits, and if the grains had been broken during their transportation, or in their deposition, there would be little chance of the parts remaining so near to one another, or of their keeping the same relative positions. Since this formation was deposited there has been no diastrophism in the region which could cause a cracking of sand grains, and no local movements such as faulting or slumping. Most important of all, such split grains are not found in the slides from any part of the formation except the very dense, porcelain-like caliche.

No exact figures for the force exerted by growing crystals are available. The experiments by Becker and Day show that an alum crystal can raise a 1-kilogram weight. They concluded as a result of their experimentation that "the linear force exerted is of the order of magnitude of the breaking strength of the crystal."[1]

In the case of the Nussbaum caliche considerable force must have been exerted. In the shoving aside of sand grains sufficiently to reduce the percentage of sand in the caliche from 100 to 10 per cent, considerable masses of rock must have been moved. If the rock averaged 150 pounds per cubic foot, it would require a force of 21 pounds per square inch merely to raise a 20-foot column of it. To overcome cementation in addition to raising it, a much greater force would be required.

The force necessary to split quartz, however, is much greater. Data from the Geophysical Laboratory are to the effect that the tensile strength of quartz varies from 1,300 megabars (18,850 pounds per square inch) to 1,600 megabars (23,000 pounds per square inch), depending on whether the force is applied at right angles or parallel to the C-axis.[2] These figures probably do not represent the minimum forces actually exerted, because calcite crystallizing at the outer end of a crack would have some leverage due to the length of the crack. The distances allowable for such leverages, however, are very small and would not lower the figures sufficiently to invalidate the conclusion that the force exerted by the crystallizing calcite was very great.

CONCLUSIONS

The study of the Nussbaum caliche has brought out two points on the force of crystallization: (1) Growing calcite crystals exert a force sufficient to move considerable bodies of rock material and also sufficient to split grains of quartz. (2) The force exerted is very great, the maximum in this case being about the tensile strength of quartz (18,000–23,000 pounds per square inch).

[1] G. F. Becker and A. L. Day, *Jour. of Geol.*, Vol. XXIV, No. 4, p. 313.

[2] R. B. Sosman, personal communication.

THE ANCESTRAL ROCKY MOUNTAINS OF COLORADO AND NEW MEXICO[1]

FRANK A. MELTON
University of Chicago

ABSTRACT

A detailed comparison of the Permo-Pennsylvanian strata in the Sangre de Cristo, San Juan, Crested Butte, and other areas of southwestern Colorado and north-central New Mexico, shows that the Permo-Pennsylvanian mountains in southwestern Colorado occupied the position of the present San Luis Valley, La Garita Hills, Cochetopa Hills, Vernal Mesa, Uncompahgre Plateau, and probably extended even farther to the northwest. This ancient highland is named the "San Luis Mountains."

There are many references in geological literature to the ancestral Rocky Mountains of Permo-Pennsylvanian age in Colorado and northern New Mexico.[2] Many investigators are of the opinion that a mountain mass of considerable size occupied approximately the present position of the Front Range of Colorado and that it gave rise to the large thickness of coarse, red conglomerates and associated beds of continental origin that are found in the Fountain conglomerate and overlying red beds of this region. At the southern end of the Wet Mountains in Colorado the coarse conglomeratic nature of the Badito formation shows that mountains existed there also in Permo-Pennsylvanian time though they were probably only a small isolated group. Likewise the coarse nature of the red Wyoming formation of the Leadville and Tenmile area points to the probable existence of a mountainous area to the west in the position of the present Sawatch Range. Farther south in the Sacramento

[1] The writer is indebted to Professor R. T. Chamberlin, of the University of Chicago, for important suggestions leading up to this investigation, and to Dr. P. G. Worcester for valued criticism and help.

[2] Some with a direct bearing on the problem are: W. T. Lee, *Smithsonian Misc. Coll. 69*, No. 4, 1918; A. J. Tieje, *Jour. Geol.*, Vol. XXXI, No. 3, April-May, 1923; J. Henderson, *Colorado Geol. Survey, Bull. 19*, 1920; R. M. Butters, *Colorado Geol. Survey, Bull. No. 5*, 1913, pp. 62–94. C. W. Tomlinson, "The Origin of the Red Beds," *Jour. Geol.*, Vol. XXIV (1916), pp. 153–79, 238–53; and various geologic atlases published by the U.S. Geol. Survey.

Mountains of southern New Mexico there seems also to have been a small high area undergoing erosion and furnishing sediments in early Permian time.

The probable existence of a much larger group of mountains than any of those listed above will be shown by a correlation of the stratigraphic evidence from various neighboring areas in southwestern Colorado and north-central New Mexico. This large mountainous tract occupied the position of the present San Luis Valley, Cochetopa Hills, La Garita Hills, Vernal Mesa, Uncompahgre Plateau, and probably extended still farther to the northwest. The southern extremity was probably about at the present southern end of the Culebra Range in New Mexico (Fig. 1). The districts which furnish the evidence for the existence of this large area of the southern Ancestral Rocky Mountains are the Sangre de Cristo Range, San Juan region, Uncompahgre Plateau, the Aspen and Crested Butte district, and the large region between these separate areas.

Following is a brief summary of the evidence for each district and a statement of its bearing on the problem as a whole.

SANGRE DE CRISTO RANGE

In this range from La Veta Pass to Salida, Carboniferous clastic beds of varying degrees of coarseness indicate proximity to mountains at the time of origin. The arkosic and conglomeratic nature of the Sangre de Cristo conglomerate, its great apparent thickness (about 13,000 feet), and the apparent overlap of the lower part by the upper part of the conglomerate—by which the upper part rests directly on the pre-Cambrian granite surface—all point to the existence of mountains in this area during Permo-Pennsylvanian time. The evidence is particularly strong for the existence of steep mountains very close to this area during Permian time since the upper part of the Sangre de Cristo conglomerate (probably of Permian age) is unusually coarse and has a maximum thickness of about 5,000 feet. Bowlders of pre-Cambrian granites up to 8 feet in diameter have been found and the average size is probably between 1 and 2 feet. Near the west edge of the present Sangre de Cristo range these coarse conglomerates are well developed and rest on granite; but they disappear to the east within a very few miles.

In the Culebra Range on the South Fork of the Purgatoire River in southern Colorado,[1] the red beds are at least 11,537 feet thick and contain many coarse conglomerates composed of cobbles which measure up to 8 inches or more in diameter and which consist of many varieties of crystalline and metamorphic rocks.

In the plains east of the Sangre de Cristo Range in Colorado and New Mexico, where the red beds have been exposed by erosion, they are much finer grained than in the mountains and are not known to be more than about 1,000 feet thick.[2] They are composed largely of red sandstones, shales, and occasional layers of pebbly conglomerates.

Considering the Sangre de Cristo Range as a whole it seems evident that a mountainous area existed close to it on the west side during Permo-Pennsylvanian time and that these red beds represent piedmont alluvial fans and alluvial plains that formed along its eastern side.

CRESTED BUTTE—ASPEN REGION

A comparison of the Crested Butte and Aspen districts shows that the Carboniferous sediments in these areas were partly derived from a high area to the south. The sediments in the Crested Butte district are coarser than in the Aspen district. While it seems that the upper and perhaps the coarsest part of the section has been removed near Crested Butte, the uppermost beds still existing consist of arkoses and coarse conglomerates composed of pre-Cambrian materials. On the other hand nothing coarser than grits and fine conglomerates has been mentioned in the Aspen section. The greater thickness of the Aspen Carboniferous section over that of the Crested Butte district (7,600 feet as compared with 5,550 feet) is probably due to removal of the upper part of the section in the Crested Butte district by erosion prior to Jurassic time.

UNCOMPAHGRE PLATEAU REGION

To the southwest of the Uncompahgre Plateau near Gateway, Colorado, in the canyon of West Creek,[3] the Cutler formation (of

[1] W. T. Lee, *U.S. Geol. Survey, Prof. Paper 101*, 1917, p. 41.

[2] A. J. Tieje, *Jour. Geol.*, Vol. XXXI (1923), p. 197, footnote; W. T. Lee, *Jour. Geol.*, Vol. X (1902), p. 55, and Vol. IX (1901), pp. 343–52.

[3] W. Cross, *Jour. Geol.*, Vol. XV (1907), pp. 662–66; R. C. Coffin, *Colo. Geol. Survey Bull. 16*, 1921, pp. 56–60.

Permian age) overlaps all underlying formations and rests directly against the pre-Cambrian crystalline rocks of the plateau. It is

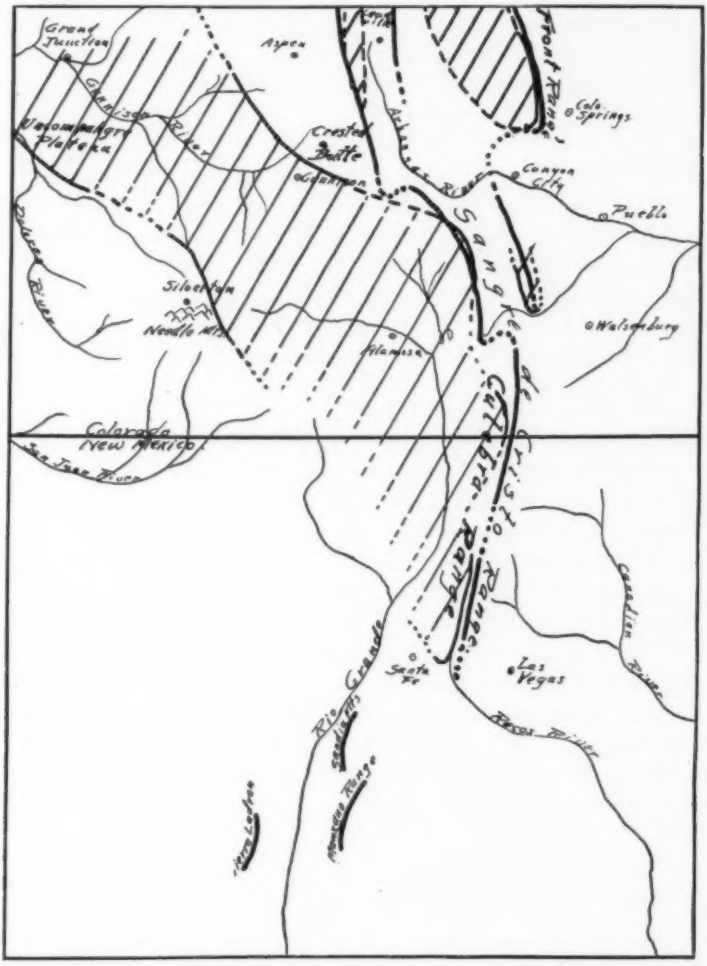

FIG. 1.—The ancestral Rocky Mountains of southwestern Colorado and north-central New Mexico. The oblique lines indicate the region which probably stood high or in which more or less connected mountain masses existed during Pennsylvanian and Permian time.

largely arkose and conglomerate and contains an abundance of poorly rounded cobbles and bowlders of granitic rocks. The largest bowlders are about 1½ feet across and the thickness of the formation is at least 879 feet. Farther south in the Dolores River region the same formation is somewhat thinner and is much finer grained. Here coarse conglomerates are entirely lacking.

SAN JUAN AREA

In the San Juan area it is clear that the source of supply for the Carboniferous beds was to the east of the area in which these formations now outcrop. The bright-red Cutler formation is prevailingly arkosic and coarsely conglomeratic in the Needle Mountains, where it contains an abundance of cobbles and bowlders of pre-Cambrian rock, but farther west toward the Dolores River this formation becomes thinner and much finer grained.

OVERLAP OF LA PLATA SANDSTONE

The occurrence of La Plata sandstone (of Jurassic or Comanchean age) and Tertiary extrusive volcanic material in direct contact with pre-Cambrian crystalline rocks[1] over large areas along the Gunnison River and Black Canyon and in small isolated areas north and east of the San Juan region, when considered in connection with the other evidence adduced, suggests that this area was high and undergoing erosion in Carboniferous time. It certainly was elevated at some time prior to the deposition of the La Plata sandstone and the coarse character of the Permo-Pennsylvanian beds bordering this area together with the lack of noteworthy coarseness in beds of Triassic or Jurassic age indicates that this elevation occurred during the Carboniferous.

SOUTH END OF SANGRE DE CRISTO RANGE

In New Mexico near Santa Fe and Las Vegas the Abo formation of Permian age[2] (basal Manzano) has a probable maximum thickness of about 4,500 feet near Mora and is characteristically composed of coarse arkoses, shales, and conglomerates. Farther south

[1] W. Cross and E. S. Larsen, *U.S. Geol. Survey, Prof. Paper 90*, 1915, pp. 39–51.

[2] W. T. Lee and G. H. Girty, *U.S. Geol. Survey Bull. 389*, 1909.

near Glorieta Pass, however, the thickness has diminished to less than 1,000 feet, and still farther south the formation becomes fine grained.

CONCLUSION

On the accompanying map the lined areas indicate the probable location of this mountainous area as shown by the foregoing evidence. A solid line marks the boundaries where they can be rather definitely placed and the hypothetical connections between these known boundaries are indicated by broken lines.

For the sake of brevity and convenient reference these Permian mountains between the San Juan, Crested Butte, and Sangre de Cristo areas are named the "San Luis Mountains" from the present San Luis Valley of this region. While they include an area much larger than the San Luis Valley it is probably as appropriate as any other geographical name that could be applied.

It should be emphasized that while the principal evidence for the existence of these "San Luis Mountains" comes from rocks of probable Permian age and while consequently the mountains are believed to have reached their maximum development in Permian time, yet the evidence from rocks of Pennsylvanian age is parallel and contributory to that from the Permian strata but is not so marked. Since the thickness and coarseness of the Pennsylvanian strata seem to decrease in the same directions as the Permian strata, it is believed that mountains existed in this San Luis area at least during the latter part of Pennsylvanian time and that they were probably raised and enlarged areally by the diastrophism which occurred at the beginning of Permian time. It is to these mountains which reached their maximum development in Permian time, that the name "San Luis Mountains" is intended to apply.

REVIEWS

Structural Geology. Revised Edition. By C. K. Leith. New York: Henry Holt & Co., 1923. Pp. 290, figs. 103.

When this text first appeared, in 1913, many geologists who welcomed it enthusiastically wished that its substance had not been boiled down quite so much in the interest of economy of space. This brevity has now been remedied in the revised edition which has more than twice as many pages as the original text. Outside of the fuller treatment, the most important changes are in the general approach to the subject. In the new edition, the first part is devoted more largely to an extended description of structures in the zone of observation, while it is left to later chapters to deal with the causes of deformation and with the unseen below. By this method of treatment the author has avoided complicating his discussion of the zone of observation with speculative considerations.

No author has been more careful to bring out sharply just how much is known from direct observation, and just what is the result of inference. In the opinion of the reviewer, few things contribute more to clear thinking and confidence in the methods of analysis presented and results obtainable from their application than such a candid and insistent discrimination between what can safely be deduced from known facts and what can be deduced only with uncertainty. The spirit of proceeding safely on solid ground pervades the whole work and is constantly drilled into the student. With all the divergent ideas and theories of earth deformation floating about today to mix and menace the student of structural geology, such a thoroughly sound and impartial presentation of the fundamentals is very much needed.

Perhaps the greatest amplification has been in megadiastrophism and the ultimate forces which cause earth failure. After the description and discussion of the major units of structure, geanticlines, geosynclines, ocean basins, continents, plateaus, mountains, etc., two new chapters are introduced to give the background for the general consideration of the causes and nature of diastrophism. The first of these deals with the strength, density, and volume changes of rocks. The second presents impartially the present status of our knowledge of the structural conditions

in the interior of the earth. Naturally the author's viewpoint and path of advance into this uncertain field are of much interest.

The chapter on causes of earth failure is a judicious exposition of the leading theories developed to explain earth deformation. By far the most extended treatment has been given to the theory of deformation due to isostatic adjustments. Leith has here developed many of the numerous reasons why the geologist cannot accept the doctrine of isostasy in anything like the form advocated by its ardent supporters among the geodesists. After reading this text, it seems to the reviewer equally futile either to try to minimize the horizontal compression recorded in many regions of intense plication, or to attempt to explain the observed slaty cleavage, folding, and thrust faulting by block adjustments working to restore isostatic equilibrium. Isostatic forces are not a starting cause; while they may enter as a modifying factor in the active deformation, their rôle is essentially to follow in the train of more potent deformative forces to restore the equilibrium which these other forces have upset. Other agents start the clock and furnish most of the motive power; isostasy is one of the regulators in its running down. It is strictly secondary and subordinate. The real question seems to be, To what extent does isostatic compensation enter into the general equation of forces operating in the earth to cause deformation, and in just what way, or ways, is the reported high state of balance actually accomplished, assuming that it is a terrestrial verity as well as a mathematical interpretation? The critical analysis given in this textbook by one of the soundest of field geologists seems to the reviewer one of the best discussions of isostasy in print.

In quite a different direction, some geologists may wish perhaps that more attention had been given to the hypothesis of rearrangement and reorganization of material in favor of greater density under the pressures existing within the earth. With the high density in the interior of the earth due in part to condensation under compression, either with or without appeal to the newer ideas of the constitution and evolution of matter, the possibilities of volume shrinkage and crustal shortening of the earth may well be much greater than what has been allowed on the more familiar basis of cooling alone.

An entirely new chapter has been introduced on landslides, creep, mine subsidence, and deformation due to local changes in volume. While the old edition, in common with most textbooks in structural geology, was mainly confined to the deformation of hard rocks, at least by implication, in the present edition relatively more emphasis is placed on the deformation of soft and unconsolidated rocks. Recognition of the fact that

certain structures now existing in hard rocks were formed there when the rocks were in different physical condition entails inferences as to the diastrophic history of quite a different kind from those based on the assumption that the rocks were crystalline and competent at the time of deformation. As the importance of this is becoming increasingly apparent the criteria for the separation of structures formed in hard rocks from those formed in unconsolidated sediments are presented in detail.

Two new chapters, one on field methods, and the other a series of very useful summaries, by Edward Steidtmann, of the experimental work which has been done in structural geology complete the book.

The general feeling which the reader has after finishing this volume is that when you have got what Leith says, you have it clearly and know pretty well its value. The frank, open-minded spirit of the author, coupled with his painstaking efforts to train the student in correct thinking and safe reasoning, makes this book admirable alike as a geologic habit-former and as a textbook on structural geology.

R. T. C.

Geochronologische Studien über die spätglaziale Zeit in Südfinnland. By MATTI SAURAMO. Bull. Comm. Géol. de Finlande, No. 50, 1918; also Fennia, Vol. 41, No. 1. Pp. 44, pls. 4, figs. 5.

Studies on the Quaternary Varve Sediments in Southern Finland. By MATTI SAURAMO. Bull. Comm. Géol. de Finlande, No. 60, 1923; also Fennia, Vol. 44, No. 1. Pp. 164, pls. 10, figs. 22.

The former paper deals mainly with the retreat of the last ice sheet in southern Finland. By means of a large number of measurements of sections of annually banded or varved clay, by moraines, striae, etc., the rate of the ice retreat is determined and lines indicating the position of ice edge every one hundred years, and in the southern part every ten years, are constructed. The discussion of general problems is devoted particularly to changes in the rate of retreat of the ice border, connections on long distances, relationship between the properties of the varved clay and the rate of ice retreat, and the melting of the land ice. The views expressed are more or less modified in the latter paper.

The latter paper forms a continuation of the former one, the field examined now having been extended much farther northward. Primarily, this paper is devoted to the stratigraphy and petrography of the varved sediments. The headings of the chapters may serve to give an idea of the contents of the paper: "Method of Working," "The Observa-

tions," "Stratigraphy of the Varve Sediments in Southern Finland," "Deposition of Sediments in Water," "Record of the Varve Sediments in Southern Finland."

Sauramo distinguishes different types of clay according to the distribution of the coarse-grained and fine-grained material in the varves. Varves in which the fineness of the material is visibly increasing upward by decrease in the number of coarse grains and a contemporaneous increase in the number of fine particles are called "diatactic varves" (p. 78). Varves in which the coarse and fine material is mixed in the whole varve or in the upper part of the varve with upward increasing proportion of fine particles, because considerable quantities of the fine material went down already during the summer, are called "symminct varves" (pp. 82, 98, 110). The degree of symmixis can be variable and the two types merge into each other. Symmixis is evidently due to relatively rapid flocculation of the fine particles caused by flocculator, easily aggregating particles, or other physical conditions favoring coagulation. Sauramo thinks that symminct structure is an indication of sea water (p. 110), and because of this view draws some conclusions regarding the late glacial geology of Fenno-Scandia (pp. 86, 117, 123–29, 158) which appear to be contradicted by other observations. The fact seems to be that not only marine and brackish-water clays are symminct, but occasionally also fresh-water clays, as, for instance, in Vermont and in northern Ontario. In order that Sauramo's use of the term "marine" may not lead to misunderstanding, it should be remarked that, although the late glacial Baltic for a time was connected with the Atlantic Ocean by straits across central Sweden, in Finland it was not even brackish from the biological point of view, judging from the absence of brackish-water fossils in the varved clays.

The rate of the ice recession is considered to have stood in direct casual relation to the topography, to the variation of deep and shallow waters (pp. 133, 135, 151), and to have been more or less independent of climatic conditions (pp. 160, 163). This view, however, may be wrong, for the fact alone that the ice edge halted in the largely submerged central Sweden, north of the south Swedish highland, clearly shows that these halts were due to climatic not to topographic conditions; and there is no reasonable cause to doubt the contemporaneity of the Swedish and Norwegian moraines with the Salpausselkäs in Finland. On the whole, climate had much greater influence upon the ice retreat than had topography.

Both papers are excellently illustrated by maps, diagrams, and

photographs, although the first one was printed during the Finnish Red War. They represent determined and highly successful studies of eminent importance both for students of Pleistocene geology and for students of sedimentation problems.

ERNST ANTEVS

Magnetic Iron Ores of East Tennessee and Western North Carolina. By W. S. BAYLEY. The North Carolina Geological and Economic Survey, Bulletin No. 32, and the Tennessee Geological Survey, Bulletin No. 29, 1923. Pp. 252, pls. 23, and text figs. 28.

Both titaniferous and non-titaniferous iron ores occur as lenses and veins in crystalline rocks, most of them in the mountainous districts, where the associated rocks are Archean. In a broad way, the deposits are usually in zones parallel to the general structure of the region, but, in a narrower sense, they form series of discontinuous lenses along lines that may be close together or widely spaced.

The principal deposits of non-titaniferous magnetite are mixtures of magnetite with hornblende and minor quantities of quartz, epidote, feldspar, calcite, and a few other minerals. Most of the material contains only 40–42 per cent of iron, and must be concentrated before smelting. The ores of the Cranberry and other mines producing magnetite of this class are associated with acid igneous rocks, including pegmatite, and not with basic igneous rocks; and Bayley believes that the ores have been deposited from ascending hot solutions coming from an augitic pegmatite magma.

The titaniferous magnetites of the state are not worked, and little detailed information could be obtained concerning them. All are associated with basic rocks. In some of them it is noteworthy that rutile is present, sometimes in considerable abundance.

E. S. B.

Zinc Deposits of Eastern Tennessee. By MARK H. SECRIST. Tennessee Geological Survey, Bulletin 31. Nashville, 1924. Pp. 165, pls. 24, figs. 14, geological map.

After outlining the general geology of the region, which is typically Appalachian, and describing the ore and gangue minerals, the author takes up the many scattered prospects and mines, and gives a statement of the existing conditions together with a brief historical sketch wherever

such is of consequence. The only mine of importance working at the time the field work was done was the Mascot mine, about 8 miles north of Knoxville, from which comes almost the entire zinc production of Tennessee.

The author infers the following conditions from the microscopic relations: contemporary intergrowths of sphalerite and galena; zonal and concentric arrangement of sphalerite; replacement of chert by sphalerite; replacement of dolomite by sphalerite and pyrite; replacement of country rock by dolomite, sphalerite, and galena; recrystallization of country rock into coarse-grained dolomite; and a cementation of breccia by sphalerite. He decides that the various minerals were not deposited independently of one another, but that the periods of formation were overlapping and in part contemporaneous. As to genesis of the ores, the author agrees in the main with previous writers (Watson, Purdue) in that the source is considered to be the Paleozoic sediments, and that the metals have been leached during the erosion of all these sediments, but principally the Knox dolomite. The metals were then concentrated in their present location by meteoric waters circulating at shallow depths along trunk channels which were in many cases fault zones. The chemical explanations offered for the solution and redeposition are those developed by C. E. Siebenthal for the Missouri-Oklahoma field.

E. S. P.

The Geology and Invertebrate Paleontology of the Comanchean and "Dakota" Formations of Kansas. By W. H. TWENHOFEL. State Geological Survey of Kansas, Bulletin 9, 1924. Pp. 135, pls. 23.

The Comanchean and "Dakota" formations in southern Kansas consist of the Cheyenne sandstone, the Belvidere shale and sandstone (the two lowest members of the "Medicine beds" and the Kiowa shale), and the "Dakota" clay and sandstone (the two upper members of the "Medicine beds"). In the northern and central part of the state only the Belvidere (Mentor) and "Dakota" are recognized.

The sequence of events during the deposition of these formations is as follows:

1. Continental deposition by streams and winds on a coastal plain in a dry or semiarid climate—the Cheyenne sandstone
2. Kiowa-"Dakota" deposition
   a) Advance of shallow sea water—Kiowa deposition

b) Retreat of the shore line and continental deposition in central and northern Kansas
c) Northward advance of the shore line—Mentor deposition
d) Retreat of the sea—post-Mentor continental deposition

Parts of the "Dakota" are the terrestrial equivalents of the marine Kiowa-Mentor. The marine beds are an extension of the Washita of Texas. Dr. Twenhofel favors drawing the base of the Upper Cretaceous at the bottom of the Washita (Cenomanian of Europe), thereby including all of these formations in the Upper Cretaceous.

Seventy-eight species and varieties of invertebrate fossils are described and illustrated.

L. F. A.

Inlandsisens Avsmältning. I. Sydvästra Jämtland. Akademisk Avhandling. Av KJELL ERIKSSON. Särtryck ur Sveriges Geologiska Undersöknings Årsbok 6 (1912). Stockholm, 1914.

Bidrag till Västra Jämtlands Senglaciala Geologi. Akademisk Afhandling. Af GUSTAF FRODIN. Särtryck ur Sveriges Geologiska Undersöknings Årsbok 5 (1911). Stockholm, 1913.

Silicium als Vertreter des Kohlenstoffs organischer Verbindungen. Von ARTUR BYGDEN. Uppsala, 1916. Almqvist and Wiksells Boktryckeri-A.-B.